Renewable and Sustainable Energy Reviews 16 (2012) 6384–6422

Contents lists available at SciVerse ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

Fresh water production from/by atmospheric air for arid regions, using solar energy: Review

A.M.K. El-Ghonemy *

Engineering College, Al-Jouf University, KSA, Saudi Arabia

ARTICLE INFO

Article history:
Received 31 March 2012
Received in revised form
23 June 2012
Accepted 25 June 2012
Available online 1 September 2012

Keywords:
Fresh water
Atmospheric air
Humidification–dehumidification
Review

ABSTRACT

Shortage of drinking water is chronic, severe, and wide-spread in the regions of Northern Africa, Middle East, and Central and Southern Asia. Conventional processes like MSF and RO require large amounts of energy in the form of thermal energy (for MSF) or electric power (for RO). Most desalination plants using these technologies are fossil-fuel driven. This results in a large carbon footprint for the desalination plant, and sensitivity to the price and availability of oil.

Decentralized water production is important for regions which have neither the infrastructure nor the economic resources to run MSF or RO plants and which are sufficiently distant from large scale production facilities that pipeline distribution is prohibitive. Many such regions are found in the developing world in regions of high incidence of solar radiation. Accordingly, the problem of providing arid areas with fresh water can be solved by extracting water from Atmospheric air.

The Atmospheric air is considered a large and renewable source of fresh water. The atmosphere contains about 12,900 km^3 of fresh water, whereas liquid water resources of inhabited lands is about 12,500 km^3.

In this paper, atmospheric water vapor processing (AWVP) technology is reviewed. These processors are machines which extract water molecules from the atmosphere, ultimately causing a phase change from vapor to liquid. Three classes of machines have been proposed. These classes are either cool a surface below the dew point of the ambient air, concentrate water vapor through use of solid or liquid desiccants, or induce and control convection in a tower structure. The review is extended to cover different humidification and dehumidification (H–DH) techniques in which air is used as a medium to carry water in the form of vapor. The study concentrates on the extracting potable water from air especially with respect to the remote/rural arid places. Finally, different technological processes to extract water from the ambient air using solar energy as a power source are focused with discussing their strengths and limitations.

Contents

* Tel.: +966 595188023.
E-mail address: amghonemy@yahoo.com

1364-0321/$ - see front matter © 2012 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.rser.2012.06.029

1. Introduction

The Millennium development goals set by the United Nations highlight the critical need of impoverished and developing regions of the world to achieve self-sustenance in potable water supply. Desalination systems are essential to the solution of this problem. However, conventional desalination technologies are usually large-scale, technology intensive systems most suitable for the energy rich and economically advanced regions of the world. They also cause environmental hazards because they are fossil-fuel driven and also

Nomenclature

A	Surface area, m^2
A_r	is radiating surface area (m^2) of the condenser
AWVP	atmospheric water vapor processors
C_C	is condenser material specific heat (J/kg K)
C_w	liquid water specific heat (4180 J/kg K)
D	Day
H–DH	humidification–dehumidification
L	liter
M	is condenser mass (kg)
m	condensed water mass (kg)
q_{rdb}	is direct beam radiation
q_{ril}	is long-wave diffuse incoming radiation
q_{ris}	is short-wave diffuse incoming radiation
q_{ro}	is outgoing radiation of the condenser
σ	is the Stefan–Boltzmann constant (5.67×10^{-8} W/m^{-2} K^{-4})
ε_c	is condenser emissivity.
q_{ro}	the radiation from the condenser
ω	absolute humidity

because of the problem of brine disposal. In the following section these conventional desalination technologies are introduced and their drawbacks are discussed [1].

1.1. Limitation of water resources

Three essentials commodities for human beings to live are shelter, clothing and food. Of the three commodities, the third is consumed by people orally. So, prime importance is given to its clean and non-infecting nature. Water is one of the very important items, in every day's life, which is not only used to cook food but also to drink and clean. In accordance to one of the surveys of World Health Organization (WHO), 97.5% of water on the earth is salty and the remaining 2.5% is fresh water. Also 70% of the fresh water is frozen in the polar icecaps and the other 30% is either as soil moisture or in underground aquifers. This leads to an estimate of less than 1% of the world's fresh water (or about 0.007% of all water on earth) is readily accessible for direct human use. Naturally, water scarcity is not a new problem. Contaminated drinking water is dangerous to health. A recent study by Lorna of WHO indicates that every eight second a child dies from a water related disease and that each year more than 5 million people die from illnesses linked to unsafe drinking water or inadequate sanitation. Household water filters cannot remove all the parasites, viruses, bacteria and heavy metals. These factors indicate the need of developing or identifying appropriate techniques suitable for an arid place especially situated at remote villages in developing countries in order to (1) produce good clean potable drinking water, and (2) to conserve water and energy [1].

1.2. Conventional desalination technologies

Desalination of seawater or brackish water is generally performed by either of two main processes: by evaporation of water vapor or by use of a semi-permeable membrane to separate fresh water from a concentrate. The most important of these technologies are listed in Table 1. In the phase-change or thermal processes, the distillation of seawater is achieved by utilizing a heat source. The heat source may be obtained from a conventional fossil-fuel, nuclear energy or from a non-conventional source like solar energy or geothermal energy. In the membrane processes, electricity is used either for driving high pressure pumps or for establishing electric fields to separate the ions.

The most important commercial desalination processes [2,3] based on thermal energy are multi-stage flash (MSF) distillation, multiple effect distillation (MED) and vapor compression (VC), in which compression may be accomplished thermally (TVC) or mechanically (MVC). The MSF and MED processes consist of many serial stages at successively decreasing temperature and pressure. The MSF process is based on the generation of vapor from seawater or brine due to a sudden pressure reduction (flashing) when seawater enters an evacuated chamber. The process is repeated stage-by-stage at successively decreasing pressure. Condensation of vapor is accomplished by regenerative heating of the feed water. This process requires an external steam supply, normally at a temperature around 100 °C. The maximum operating temperature is limited by scaling formation, and thus the thermodynamic performance of the process is also limited. For the MED systems, water vapor is generated by heating the seawater at a given pressure in each of a series of cascading chambers. The steam generated in one stage, or "effect," is used to heat the brine in the next stage, which is at a lower pressure. The thermal performance of these systems is proportional to the number of stages, with capital cost limiting the number of stages to be used. In TVC and MVC systems, after vapor is generated from the saline solution, it is thermally or mechanically compressed and then condensed to generate potable water.

The second important class of industrial desalination processes are membrane technologies. These are principally reverse osmosis (RO) and electrodialysis (ED). The former requires power to drive a pump that increases the pressure of the feed water to the desired value. The required pressure depends on the salt concentration of the feed. The pumps are normally electrically driven [3]. The ED process also requires electricity to produce migration of ions through suitable ion-exchange membranes. Both RO and ED are useful for brackish water desalination; however, RO is also competitive with MSF distillation processes for large-scale seawater desalination. The MSF process represents more than 90% of the thermal desalination processes, while RO process represents more than 80% of membrane processes for water production. MSF plants typically have capacities ranging from 100,000 to almost 1,000,000 m^3/day [2,4]. The largest RO plant currently in operation is the Ashkelon plant, at 330,000 m^3/day [2,4].

Other approaches to desalination include processes like the ion-exchange process, liquid–liquid extraction, and the gas hydrate process. Most of these approaches are not generally used unless when there is a requirement to produce high purity (total dissolved solids <10 ppm) water for specialized applications. Another interesting process which has garnered much attention recently is the forward osmosis process [2]. In this process, a carrier solution is used to create a higher osmotic pressure than that of seawater. As a result the water in seawater flows through

Table 1
Conventional desalination technologies [2].

Phase-change processes	Membrane processes
1-Multi-stage flash (MSF) 2-Muiltiple effect distillation(MED) 3-Vapor compression(VC) 4-Solar stills	1-Reverse osmosis 2-Electrodialysis(ED)

the membrane to the carrier solution by osmosis. This water is then separated from the diluted carrier solution to produce pure water and a concentrated solution which is sent back to the osmosis cell. This technology is not yet proven commercially.

1.3. Limitations of conventional desalination technologies

Conventional processes like MSF and RO require large amounts of energy in the form of thermal energy (for MSF) or electric power (for RO). Most desalination plants using these technologies are fossil-fuel driven. This results in a large carbon footprint for the desalination plant, and sensitivity to the price and availability of oil. To avoid these issues, desalination technologies based on renewable energy are highly desirable. Solar energy is the most abundantly available energy resource on earth.

Solar desalination systems are classified into two main categories: direct and indirect systems. As their name implies, direct systems use solar energy to produce distillate directly using the solar collector, whereas in indirect systems, two sub-systems are employed (one for solar power generation and one for desalination). Various solar desalination plants in pilot and commercial stages of development were reviewed by many authors [2,3]. In concept, solar-energy based MSF and MED systems are similar to conventional thermal desalination systems. The main difference is that in the former, solar energy collection devices are used. Some proposals use centralized, concentrating solar power at a high receiver temperature to generate electricity and water in a typical large-scale co-production scheme [3]. These solar energy collectors are not yet commercially realized. It should be noted that at lower operating temperatures, solar collectors have higher collection efficiency, owing to reduced losses, and also, can be designed to use less expensive materials. Moreover, owing to their fossil fuel dependence, conventional desalination techniques are less applicable for decentralized water production.

Decentralized water production is important for regions which have neither the infrastructure nor the economic resources to run MSF or RO plants and which are sufficiently distant from large-scale production facilities that pipeline distribution is prohibitive. Many such regions are found in the developing world in regions of high incidence of solar radiation.

The importance of decentralizing water supply was highlighted by Shanmugam et.al. [1]. For small scale applications (from 5 to 100 m^3/day water production), the cost of water production systems is much higher than for large scale systems. For RO systems, which are currently the most economical desalination systems, the cost of water production can go up to US$ 3/m^3 [1] for plants of smaller capacity. Also, RO plants require expert labor for operation and maintenance purposes. This is a clear disadvantage for small scale applications in less developed areas, particularly when compared to the H-DH system; it requires expert labor for operation and maintenance purposes.

1.4. The need for extracting water from atmospheric air

Shortage of drinking water is chronic, severe, and wide-spread in the regions of Northern Africa, Middle East, and Central and Southern Asia. The problem of providing arid areas with fresh water can be solved by the following methods [4]:

- transportation of water from other locations;
  desalination of saline water (ground and under-ground);
- extraction of water from atmospheric air.

Transportation of water through these regions is usually very expensive, and desalination depends on the presence of saline water resources, which are usually rare in arid regions.

Water is available in abundance on the earth; however, there is a shortage of potable water in many countries in the world. In many countries, non-renewable energy from oil and natural gas is used to desalinate water from sea water in multi-effect evaporators. It is also common in some places to use electric power to run reverse osmosis units for water desalination. In the first method, a large quantity of heat is required to vaporize the water, while the second method requires electric power to generate high pressure to force the water component of seawater through a membrane. Both methods consume large amounts of energy and require high skill operation. Nevertheless, these two methods, until recently, were considered as the most practical way of desalinating seawater because the Gulf countries, known for their shortage in drinking water, are also known for the availability of oil as a cheap source of energy. Due to the fossil-fuel-based energy consumption in both methods, CO_2 emission will always be an issue of environmental concern. Also there are many places where energy is too expensive to run such desalination processes. Sometimes fresh water is required at locations far from the energy grid-lines, requiring a local source of energy. Hence, even countries with rich resources of energy, such as the Gulf countries, have shown a strong interest in the desalination processes that often utilize renewable energy sources.

1.5. Why atmospheric air?

The atmospheric air is considered a huge and renewable source of fresh water. The atmosphere contains about 12,900 km^3 of fresh water, whereas liquid water resources of inhabited lands is about 12,[illegible]00 km^3 [5].

Air is composed primarily of nitrogen (78%) and oxygen (21%), containing varying amounts of water in vapor form, depending on its temperature and pressure. The amount of water in the atmosphere is calculated from its partial pressure (P) within the air mass. At a given temperature (and pressure), the partial pressure cannot exceed a certain level without condensation occurring; this is the saturation pressure (P_s). The relative humidity (RH) is then defined as the ratio of partial pressures ($RH = P/P_s$). The P_s rises in conjunction with the increase in air temperature (or pressure) and the water mass capacity of 1 m^3 of air also rises. For air at a given temperature and RH, the psychometric diagram—representing the mass fraction of water in the air at different temperatures and RH—allows the air's water saturation point to be ascertained. This is "dew temperature", the temperature at which water vapors condenses. For instance, the dew temperature of air at 20 °C and 80% relative humidity is 18 °C. The dew temperature falls to 10 °C if the RH is only 25%. More information about air properties are given in Appendix-A

On most substrata, condensation occurs in the form of droplets, representing partial wetting of the substrate by liquid water. As they expand, the droplets touch and merge, their growth becoming self-similar over time. The astonishing result is that with this growth, a substantial proportion of the medium remains dry (ideally 45%). So how can water be obtained from the air? Firstly, there are methods that allow harvesting of the obvious manifestations: fog and dew.

1.6. Water vapor in atmospheric air

Water vapor molecules are present in every cubic meter of the atmosphere. Unassociated, single water molecules or monomers are known as water vapor. Water vapor density or absolute humidity at a specific location varies with geographical location, altitude, time of day, and season. Density is usually highest near Earth's surface, close to sources of vapor like water bodies and vegetation. By volume, water vapor is 4% of the atmospheric gas mixture, and by mass it is 3% of the air. Horizontal transport of water vapor is enormous. Arid zones may have high absolute humidity even though natural

condensation mechanisms may not cause precipitation. AWVP can extract this otherwise unobtainable moisture [5].

Defining water vapor content of a moist air volume Absolute humidity or water vapor density is defined as [4]

$$d_v = M_w/V \text{ kg m}^{-3}. \tag{1}$$

where M_w is mass of water vapor (kg) and V is total volume of a moist air sample (m^3).

Although ideal for visualizing water quantity extracted from each cubic meter of air flowing through an AWVP site, d_v is little used in meteorology or dehumidification engineering because it is a volumetric measure whose value varies with pressure. Relative humidity, RH, is a temperature dependent measure because as air temperature, ta, increases, the air's water holding capacity increases. This makes AWVP well-matched as an alternative water source in water-scarce locations which have relatively high average air temperatures.

Absolute humidity at a site is determined using a sea level psychometric chart (ASHRAE 1993) if t_a and ρ_a are known. The chart shows the corresponding humidity ratio, HR, which can be converted to d_v using

$$d_\nu = \text{RH}\ \rho_a,\ \text{kg m}^{-3} \tag{2}$$

where density of dry air, ρ_a, is found in Table 4.

1.7. Collecting water molecules

Processing atmospheric water vapor into drinking water requires two steps. First, water vapor molecules are attracted to a limited volume within a container or to a surface connected to a water storage tank. A vapor pressure gradient is established so there is water vapor flux from the air to container interior or the surface. Thi[illegible] is flux of mass (water vapor molecules themselves) and energy (laten[illegible] heat contained in the gas phase of water molecules). A cooled surface, desiccants, or convection with adiabatic cooling can all cre[illegible] water vapor pressure gradients that concentrate water vap[illegible]mo[illegible]les onto a surface or into a closed volume. These thr[illegible]metho[illegible] are described in the "AWVP types" section.

1.8. Building liquid water

The second step associates or i[illegible]s individ[illegible] water vapor molecules, H2O, by hydrogen b[illegible]s into water [illegible]lymers or clusters (H_2O)c, where c is [illegible]ber [illegible] molecules. Degree of association for water vapor mo[illegible]is inv[illegible]sely proportional to temperature. Cooling a [illegible]me o[illegible]oist ai[illegible]ecreases kinetic or translational energy o[illegible]vat[illegible]vapor [illegible]ules and probability increases that neig[illegible]ring [illegible]olecules will bond into clusters forming liquid wate[illegible] (1984) stated that a near spherical cluster of ap[illegible]ximately 45 water vapor molecules exhibits bulk liquid prope[illegible].

Beysens and Milimouk [illegible] emphasized that during phase change from water vapor to liquid water there is an energy barrier to overcome. The barrier is related to tension at the liquid–vapor interface. For condensation in pure air (homogeneous nucleation) air must be chilled well below the conventional dew point. Wetting properties of a substrate reduce the energy barrier considerably, promoting heterogeneous nucleation which produces dew at the dew-point. By manipulating wetting properties, droplet pattern characteristics can enhance water collection.

1.9. Problem of latent heat release

AWVP designs must cope with latent heat or heat of vaporization released whenever water changes phase from gas to liquid. This heat must be dissipated to prevent liquid water from re-evaporating before storage.

A water vapor molecule has total energy partitioned amongst its translational, vibrational, rotational, electronic, and nuclear energies. Only translational and rotational energies concern us here. Translational or kinetic energy transfers water vapour molecule mass between locations. It is proportional to absolute temperature. Gas phase molecules are always in motion but average speed of each molecule decreases as absolute temperature decreases. Slower molecular speeds allow inter-molecular forces to act and promote hydrogen bonding.

Internal rotation of the water vapor molecule accounts for energy equal in value to heat of vaporization. When hydrogen bonding occurs between water vapor molecules, the resulting cooperative structure (like a cage, called a clathrate) of the molecule cluster does not permit internal rotation. Rotational energy is rejected and is sensed as tr[illegible]ional energy (sensible heat). This is the same quantity [illegible] heat [illegible]t was required to evaporate the water molecule. [illegible]his mann[illegible] energy is transferred by water molecules. Con[illegible]ing 1 m[illegible] of liquid water (weighing 1 g) out of ai[illegible]eleases [illegible]rgy [illegible] 2450 J at 20 °C. Compare this energy w[illegible] a 4[illegible]W lig[illegible]lb which consumes 40 J in 1 s or 2400 J in [illegible]in.

Recognizing th[illegible] coll[illegible]g wat[illegible] molecules, building liquid water polymers [illegible]d coping [illegible]h [illegible]ent heat release are common to all AWVP [illegible]v[illegible] it is tim[illegible]o consider three methods that were developed for [illegible]cessing water vapor into liquid water.

1.10. [illegible]bjectives

B[illegible]cs proce[illegible] and of Atmospheric water vapor processing (AWV[illegible]echno[illegible]gy is reviewed. These processors are machines [illegible]which ex[illegible] water molecules from the atmosphere, ultimately [illegible]g a phase change from vapor to liquid. Three classes of m[illegible] have been proposed. The machines either cool a surface [illegible]elow the dew point of the ambient air, concentrate water vapor [illegible]hrough use of solid or liquid desiccants, or induce and control [illegible]onvection in a tower structure. The review is extended to covers different humidification(H) and dehumidification(DH) techniques in which air is used as a medium to carry water in the form of vapor. The study concentrates on the extracting potable water from air especially with respect to the remote/rural arid places. Finally, different technological processes to extract water from the ambient air using solar energy as a power source are included with discussing their strengths and limitations.

2. Atmospheric water vapour processing (AWVP)

Each cubic meter of air throughout Earth's 100–600 m thick atmospheric boundary layer contains 4–25 g water vapor, potentially allowing water supplies almost anywhere people inhabit.

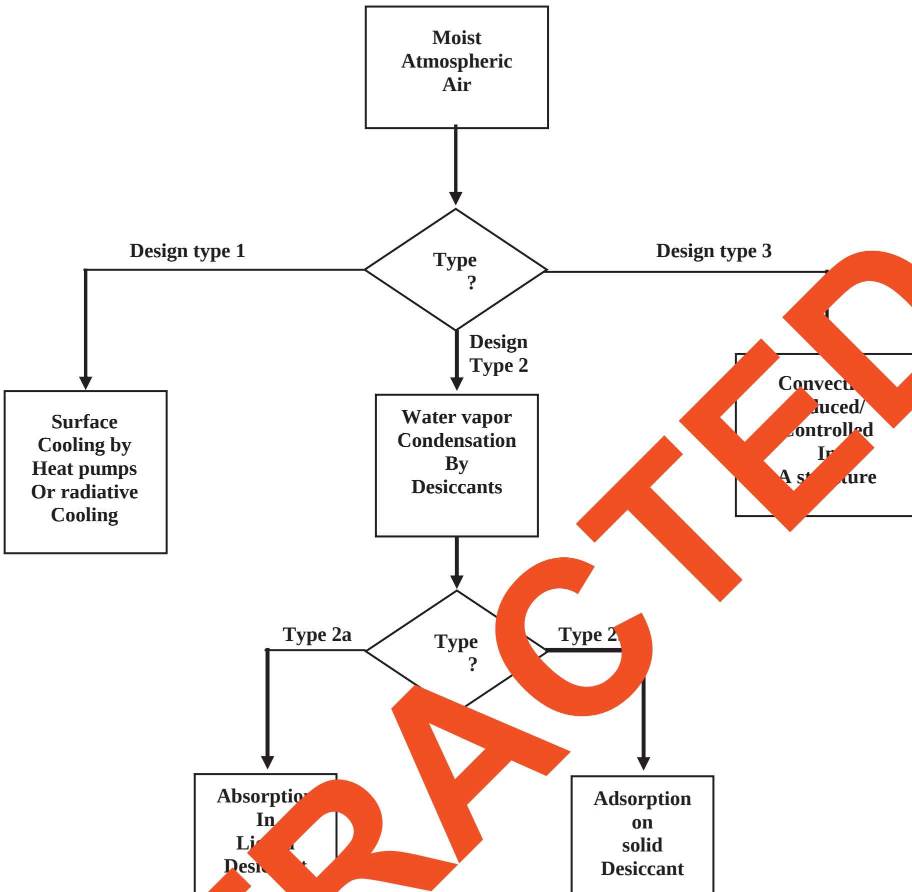
AWVP is a young technology with the potential of being made appropriate, community-managed and community-maintained in the context of developing countries. AWVP installations could be competitive with desalination plants of similar water output but

Table 2
Variation of air density with temperature (at standard $P = 101$ KPa) [4].

Temperature, t_a (°C)	Density, ρ_a (kg/m^{-3})
0	1.28
10	1.23
20	1.19
30	1.15
40	1.11

have the advantage of being simpler and less expensive to operate and maintain. Water production depends on installation size but would range from several liters to millions of liters daily.

AWVP is suitable for providing drinking water to individuals and neighborhoods of hundreds or thousands of people. Taking advantage of minimal location constraints for AWVP, the need for



Atmospheric water vapor processor design types overview [6].

Table 3
Summary of designs for atmospheric water vapor processors [6].

Design type	Author	Output (l/d)	Output (measured, hypothetical)
1. Cooled surface heat pump	ADS (1999), the Rainmaker,	25	Measured
	Gerard and Worzel (1967, 1972),	3790	Hypothetical
	Harrison (1996, 1998),	9–18	Measured
	HellstroÈm (1969)	50–170	Measured
	Kajiyama (1974)	12	Measured
	Meytsar (1997)	4275	Hypothetical
	Paton and Davies (1996)	121,000–500,000	Hypothetical (per ha equivalent)
	Poindexter (1994)	11	Measured
	Rajvanshi (1981)	643,000	Hypothetical
	Rosenthal (1999)	4	Measured
	Seymour and Bothman (1984)	5,860,000	Hypothetical
	Steiner (1999)	240,000	Hypothetical
	Zacherl (1986)	360	Hypothetical
Radiative cooling	HellstroÈm (1969)	3460–4000	Measured (per ha equivalent)
	Nilsson et al. (1994)	1200	Measured (per ha equivalent)
	Smith (1983)	5000–20,000	Hypothetical (per ha equivalent)
	Beysens et al. (1998)	1000–5000	Measured (per ha equivalent)
2. Desiccant, liquidDesiccant, solid	Lund (1973)	1.7 million	Hypothetical
	Elmer and Hyde (1986)	15,500	Measured (per ha equivalent)
	Groth and Hussmann (1979)	1000–100 million	Hypothetical (various versions)
3. Convection	Carte (1968)	108,000	Measured in mine vent. shaft
	Meytsar (1997)	2376	Hypothetical
	Starr et al. (1972)	11–22 million	Hypothetical
	Starr et al. (1974)	5–31 million	Hypothetical

Table 4
Strengths and limitations of AWVP methods [6].

Plus	Minus
Type 1: cooled surface	
Heat pump	
• Mechanical cooling is a well developed technology used for refrigeration, air conditioning, and dehumidification (Harriman, 1990) • Fairly efficient when condenser air temperature is low and cooling coil air temperature is high (Harriman). • Maintenance expertise fairly common.	• Cooling process may freeze the condensed vapor. • Frost acts as insulator to further cooling. • Air flow may be reduced when cooling elements are blocked by frost. • Special design required for dew points less than 4.5 °C. (The above four points are from Harriman.). • Finite size of cooling coil means that all of the air owing past is not cooled at same rate. There is unavoidable mixing of dried and unprocessed air within the processor (Khalil, 1993). • Power requirements fairly high. • Conventional refrigeration still uses chlorofluorocarbons (CFCs) which contribute to global high altitude ozone depletion.
Radiative cooling	
• Needs no external energy source. • Simple mechanical requirements.	• Existing technology dependent on radiation into a clear night sky heat sink. • Energy requirements fairly high for recovering potable water using desalination or distillation technology.
Type 2: desiccants	
• Well-developed technology for large scale dehumidification in industrial settings. • Can dry air to a low relative humidity. • Suitable for output air at low dew points.	• Heat of sorbtion is 5–25% of heat of vaporization and must be considered in design. • Liquid absorbents can concentrate contaminants from the atmosphere • Apart from possible contamination of the product water, contaminants can reduce the capacity of the desiccant.
Type 3: convection induced or controlled in a structure	
• Adiabatic cooling has lowest energy requirements of the three design strategies. • Natural precipitation process with extensive body of applicable meteorological theories: orographic precipitation, tornadoes, convection cells. • Engineering experience in removal of water from industrial compressed air systems is well-developed.	• Large structure (tower or tube 100 to 1000 m long) required. • No prototypes known to exist other than mine shaft analogy (Carte, 1968). • Not used for dehumidification so engineering knowledge base is limited. • AWVP designs which propose compression of air followed by expansion to cause cooling below dew point are energy intensive.

expensive water distribution infrastructure can be reduced or avoided (Table 2).

Three types of devices, which handle water vapor differently have been developed as shown in Fig. 1.

Classification of various AWVP designs discussed in the literature and in patents enables understanding the technology for further development and presenting to policy-makers (Fig. 1 and Table 3). Design types include: surface cooling by heat pumps or radiative cooling, water vapor concentrators using desiccants, and convection induced or controlled in a structure. These are compared in Table 4.

2.1. Type-1: surface cooling by heat pumps or radiative cooling

This method in the Seawater Green-house produced 3000 L of fresh water daily. Advanced Dryer Systems, Inc. (ADS) of Florida has used heat pipe technology, developed for the American space program by inventor Khanh Dinh, in The Rainmaker2 which, with an air flow of 0.1 $m^3\,S^{-1}$, can produce 25 L of water/day when air temperature is 27 °C and relative humidity is 60% (absolute humidity, $d_v = 15.7\ g\,m^{-3}$). Chlorodifluoromethane is used as refrigerant in the $38 \times 33 \times 54$ cm machine weighing 27.5 kg which has a coefficient of performance of 3.2, consuming 480 kWh to extract 1 m^3 of fresh water from the atmosphere. Recognizing the trend to minimize the use of fluorocarbon-based refrigerants, some researchers used thermo-electric (Peltier) heat pumps. Table 5 compares surface cooling to desiccant methods. The energy and mass cascade of a heat pump based water vapor processor is shown in Fig. 2. Heat pumps are used to cool surfaces so water vapor can condense and be collected.

This approach is subdivided into three categories depending on the heat sink used. Those systems transporting a critical amount of energy from the cooled surface into ambient air are using a sub-aerial heat sink. A submarine heat sink is used by systems depending on deep cold ocean water for cooling. Only one case of an underground or subterranean heat sink was found. Energy (sensible heat) is transferred away from moist air flowing past the cooled surface of the atmospheric water vapor processor. Air cooling rate is governed by temperature differences between condenser surfaces and air. Latent energy flux results when water molecules change phase from vapor to liquid. Latent heat passing to the air parcel being processed is proportional to amount of water vapor condensed. Processor cooling capacity must take this heat into account so newly condensed water is not evaporated. Efficient water vapor processing using a heat pump system maximizes the ratio

$$n = Q_L / Q_L + Q_s \tag{3}$$

where Q_L is latent heat, Q_s is sensible heat and $(Q_L + Q_s)$ is enthalpy, or total energy of an air parcel at constant pressure. Maximizing n requires sensing temperature and humidity. Feedback from sensors adjusts air-flow and cooling rate to cool incoming moist air, minimizing Q_s. There is no benefit in further cooling the flowing air after it is saturated and condensation starts collecting on the cooled surface.

Additional energy for cooling is wasted converting latent heat to sensible heat that would be carried away in the air stream. This is unlike still air, for which deeper cooling below the dew-point reduces water holding capacity and wrings out additional moisture with each degree drop in temperature. Radiative cooling.

Table 5
Comparison of surface cooling by heat pump and desiccant technologies [6].

Type 1: surface cooling by heat pump	Type 2: desiccants
– Establish vapor pressure gradient by cooling air below dew point causing water vapor to condense on heat exchanger surface. – Refrigeration and air conditioning technology.	– Low water vapor pressure at desiccant surface creates vapor pressure gradient which attracts water molecules from the air. – Wide range of commercial/industrial uses for drying air at atmospheric pressure. Moisture removal by heating to 50–260 °C.
• Direct contact (air washers, cooling towers). • Cooling and dehumidifying coils.	• Air flow removes moisture. • Cool desiccant to start attracting water molecules again.
The lower the temperature, the drier the air becomes.	High holding capacity (up to 1100% of dry mass). More desiccant removes more moisture.
Two types • Direct expansion of refrigerant gas (for smaller air flows such as residential or commercial rooftop air conditioners).	Two types • Adsorbents (solids)-water molecules simply added to surface. • Absorbents (liquids) ± water molecules [illegible]ated into substance via physical or chemical changes.
– Can cool air to 6–7 °C. – Difficult to achieve dew points below 4.5 °C because of uneven cooling of air. Some air near heat exchanger may be cooled below freezing temperature of water.	
• Chilled liquid (for larger air flows such as water coolers for commercial/industrial buildings or other large installations), liquid is typically water, glycol, or brine.	Five configurations
– Chilled liquid system allows control at low temp. – Cool almost to 0 °C without freezing condensate. – equalizes compressor and condenser loads.	• Liquid spray tower larger installations. • Solid packed tower smaller installations. • Rotating horizontal bed. • Multiple rotating bed. • Rotating desiccant wheel-all installation scales, laminar air flow, lowest energy requirement, use for solids and liquids.
	Most efficient [illegible] desiccant having • High moisture capacity. • Low mass.
Efficiency highest when • Condenser air temp. is low. • Inlet air temperature is high. • Air moisture level is high.	Performance best with lower inlet temperatures, inlet air may need pre-cooling. Preferred method when – Latent load is large in comparison to sensible load.
Condensate may freeze	• Use when absolute humidity is high. • Energy cost to regenerate (cool) desiccant is low compared to chilling a surface below the dew point. • Air dew point is below 0 °C.
• Heat transfer is reduced. • Frost clogs coil, airflow reduced.	Filtration of reactivation air required. Filters need regular replacement.
Cooling capacity must al[illegible]tent h[illegible]sion to sensible heat.	• Dust kept out of solid desiccant. • Organic vapors kept away from solid desiccant.
	Latent heat causes processed air to be warmer than incoming air. Heat of sorption is 5–25% of latent heat of water. Relatively slow air flow required. Equipment lifetime 15–30 years. Desiccant operating lifetime 10,000–100,000 h.
Filtration of inlet air required to keep heat exchanger surfaces clean. Filters need regular replacement. May need frost melting cycle (no dehumidification occurs). Efficiency is defined by the coefficient of performance, C_P.	Design must allow for operation of desiccant cycle.
	Desiccants are one type of sorbent which are particularly useful for attracting water molecules. Desiccant may also attract unwanted molecules (pollutants, contaminants, organic vapors, microbes).
C_p=energy removed from air stream/energy invested in compressor and fans.	Although this trait can be exploited in dehumidification it is undesirable for AWVP for potable water.
Typical C_P is 2.0–4.5	

Eliminating energy costs for cooling surfaces below the dewpoint is possible. AWVP techniques using radiative cooling to lower surface temperature below the dew point of adjacent air (Fig. 3) are described by many authors[5]. Resulting in, significant advances in understanding radiative cooling, dew formation and application of these processes to water supply devices.

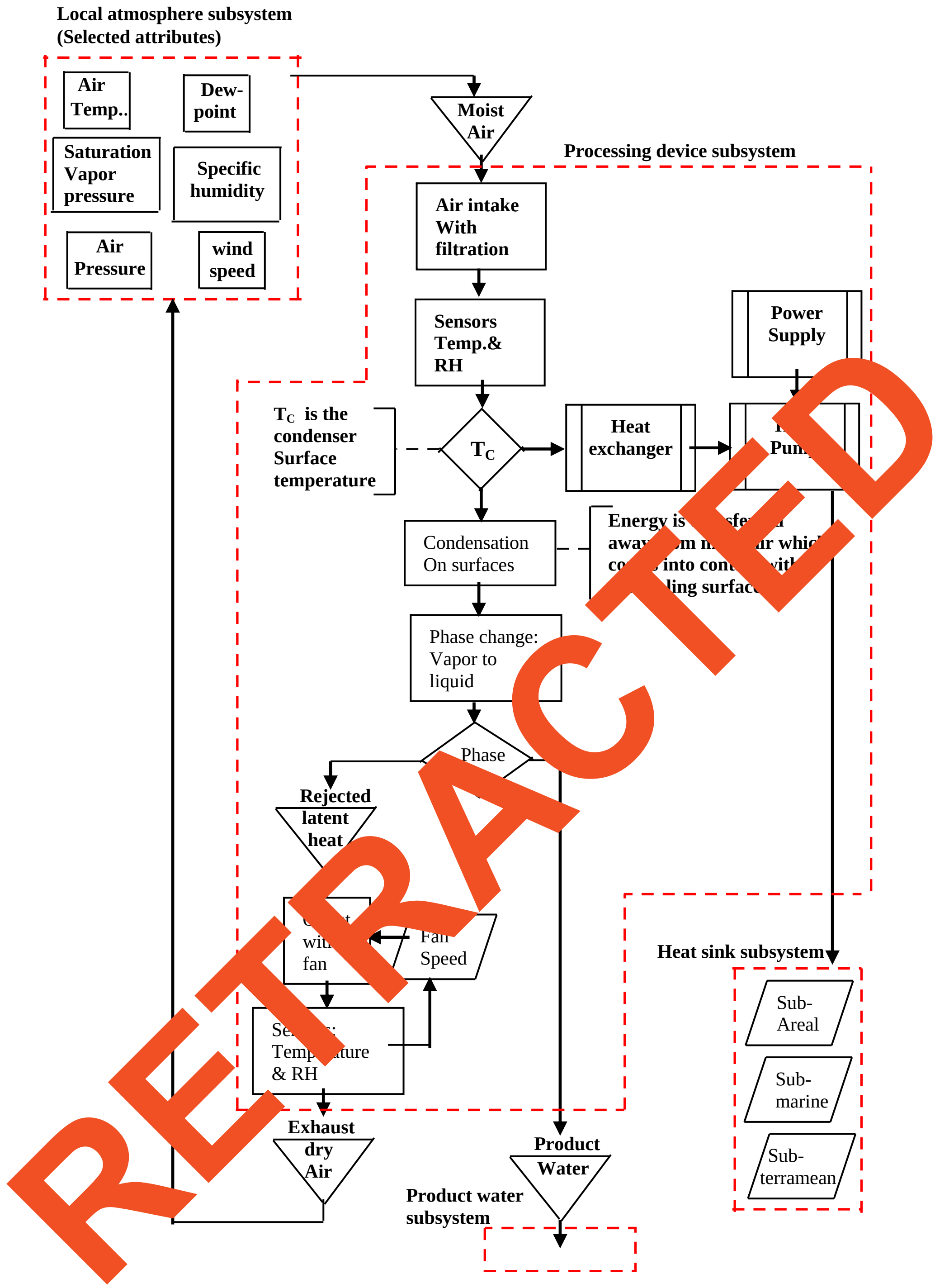


Fig. 2. Design type 1: heat pump based system for condensing atmospheric water vapor shown as an energy and mass cascade [6].

2.1.1. *Condenser heat transfer balance equation*

This is fundamental to dew collector designs. Change in heat of the radiator/condenser surface on the left-hand side of the equation balances the right-hand side heat transferred to or from the condenser surface by various physical processes so that[5]

$$\frac{dt_c}{d\tau}(Mc_c + mc_w) = q_{rt} + q_c + q_{fg} \tag{4}$$

where tc is condenser temperature (°C), t is time (s), M is condenser mass (kg), m is condensed water mass (kg), C_C is condenser material specific heat (J/kg K), and C_w is liquid water specific heat (4180 J/kg K).

On the right-hand side, three terms represent various forms of radiative heat transfer per unit time (W). Total time rate of heat transfer is denoted by q_{rt}, q_c is heat exchange with air, and q_{fg} is power gain from latent heat converted to sensible heat. The three right-hand side terms can be defined in detail. Thus

$$q_{rt} = q_{rdb} + q_{ril} + q_{ris} - q_{ro} \tag{5}$$

where q_{rdb} is direct beam radiation, q_{ril} is long-wave diffuse incoming radiation, q_{ris} is short-wave diffuse incoming radiation,

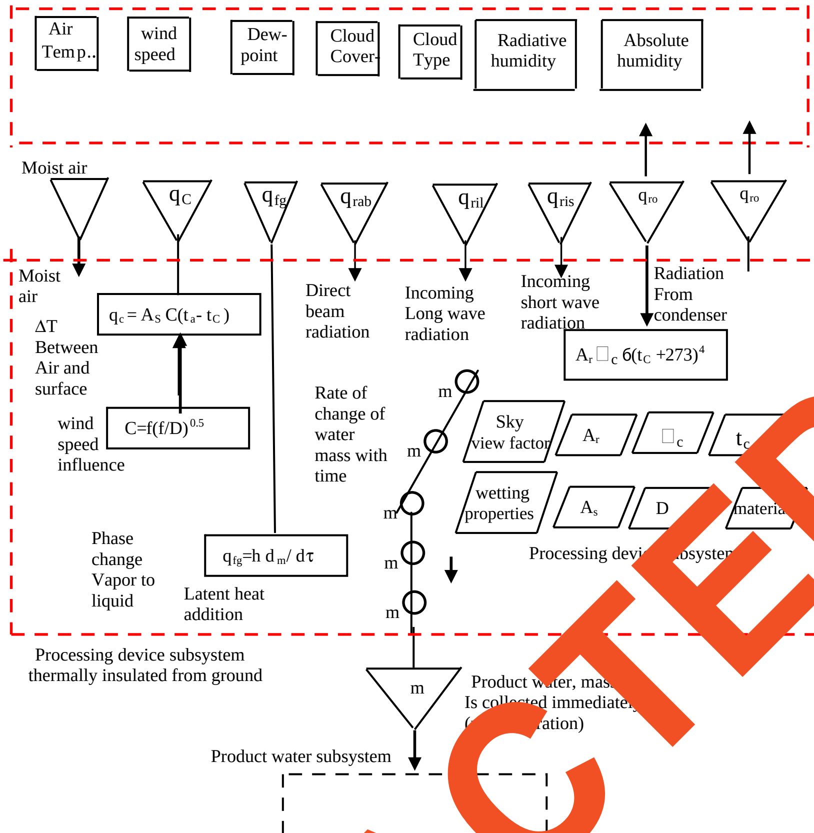


Fig. 3. Design type 1: radiative cooling system for condensing atmospheric water vapor depicted as an energy and mass cascade [6].

Table 6
Absorption-regeneration processes and improved ones [10].

Absorption-regeneration cycle processes [	Absorption-regeneration improved cycle [8]
Process 1–2: isothermal absorption of water vapor from moist air.	Process 1–2: isothermal absorption of water vapor from moist air.
Process 2–3: constant concentration heating of the absorbent.	Process 2–3: variable concentration heating of absorbent.
Process 3–4: constant pressure regeneration of absorbent.	Process 3–4: isothermal regeneration of absorbent.
Process 4–1: constant concentration cooling of absorbent.	Process 4–1: variable concentration cooling of absorbent.

and q_{ro} is outgoing radiation from the condenser. Models for estimating q_{rdb}, q_{ril}, and are Beysens and Milimouk [5].

The radiation from the condenser q_{ro} which is the key to providing a cooled surface for condensation of dew, is

$$q_{ro} = A_r \varepsilon_c \sigma (t_c + 273)^4 \tag{6}$$

where A_r is radiating surface area (m^2) of the condenser, σ is the Stefan–Boltzmann constant ($5.67 \times 10^{-8}\ W/m^{-2}\ K^{-4}$) and ε_c is condenser emissivity. Heat exchange by convection and conduction between condenser and air is

$$q_c = A_s c(t_a - t_c) \tag{7}$$

where A_s is condenser surface area from which heat exchange occurs, C is a heat transfer coefficient, and t_a is air temperature. Influence of air flow across the surface on amount of condensation that is produced on the radiator/condenser is accounted for in the model by the coefficient

$$C = f\sqrt{V/D}, \quad \left(W\ K^{-1}\ m^{-2}\right) \tag{8}$$

where, V ($m\ s^{-1}$) is air velocity and f=4 ($W\ K^{-1}\ m^{-2}\ S^{0.5}$) is an empirical factor for flow parallel to a plane with size D (m). Time rate of heat transfer attributable to enthalpy of vaporization (latent heat of condensation) of water is represented by

$$q_{fg} = h\frac{dm}{d\tau} \tag{9}$$

where h is enthalpy of vaporization of water (2.26×10^6 J/kg) and dm/dt represents condensation rate. This is non-zero only if $P_w > P_{ws}(t_c)$. where P_w is water vapour partial pressure and P_{ws} (t_c) is vapour pressure at the condenser surface when condensation begins. A vapour pressure gradient must exist for water molecules to flow from the air to the cooled surface where newly condensed water droplets are collected.

Table 7
Ranking of sorption characteristics for relative humidity, RH > 50% and air temperature, t_a=22 °C. Best performance is ranked number 1 [6].

Adsorbents	Absorbents
1. PSSASS	1. LiCl (100% at RH=90%)
2. Slica gel	2. Triethylene glycol (98% at RH=90%)
3. Activated carbon	–
4. Activated alumina	–
5. Molecular sieve	–

Dew collection continuously throughout night and day is the goal of the Swedish and French researchers. They are zeroing in on low-mass foils, such as polyethylene pigmented with Zn S, which is both an efficient reflector of short-wave and emitter of long-wave radiation. Condensation occurs on both sides of the sheet and degree of inclination has minimal influence on yield, expected through simulations to be 1l m, where unit area is one side of the sheet. Interestingly, the condenser heat balance equation is applicable also to surfaces cooled by heat pumps. Substitute net total time rate of heat transfer from the heat pump for q_{rt} in Eq. (4).

2.2. Type-2: water vapor concentrators using desiccants

Desiccants acting as water vapor concentrators extract water vapor from air by establishing a vapor pressure gradient causing flow of water molecules toward the desiccant surface. Desiccants that do

Table 8
Adsorbent-absorbent comparison [6].

Adsorbents	Absorbents
Solids • At given temp., solid surface vapor pressure lower than ambient air.	Liquids At given temp., liquid has vapor. pressure [illegible]er than am[illegible]t air.
Simpler system, relatively inexpensive. Usually for smaller spaces, free standing units. Solid packed tower type often used for compressed air. Low dew points (-40 °C). Use for very small, low dew point airstreams. Can dehumidify warm airstreams without loss of efficiency.	More complex system, therefore exp[illegible]ive. Usually large central system. Used at atmospheric pressure. Warm airstreams decreas[illegible]umi[illegible]ation efficiency. May be contaminated [illegible] org[illegible]vents.
Molecular sieve adsorbents can be manufactured to only adsorb water molecules (diameter 3.2 nm). Therefore can eliminate organic solvent molecules. Disadvantages: • Leakage of air between wet and dry airstreams. • High reactivation energy (and operating cost if energy is expensive).	[illegible]isadvantages: • Res[illegible]se time (long pipes, r[illegible]erve sump). • Ma[illegible]enance liquid desiccants are corrosive so improper operation such as too hig[illegible]n air veloc[illegible] which suspends droplets of desiccant in airstreams can cor[illegible] machine. [illegible] low humidity, desiccant can dry out quickly. • Relat[illegible] high [illegible]tal cost for smaller units.
Packed tower needs to be large to allow for low air velocity because proper operation needs: – Even flow throughout packed desiccant. – Protection of desiccant from lifting and shattering. – Initial deep drying but as desiccant fills up air is not dried a[illegible]uch. – Rotating horizontal bed has higher air flow in a compact [illegible]e.	
At same t_a and ϕ has lower capacity than absorbent Adsorption$=f$ (total surface area, total capillary vo[illegible] range of ca[illegible]y diameters). Implications/tradeoffs are: • If total surface area is large, have higher capacity at lo[illegible]	At same ta and ϕ has higher capacity than adsorbent. Vapor pressure, $P_w=f$ (t, 1/concentration of desiccant). Implications of this are: • As desiccant temperature, t, increases, fewer water molecules are attracted from the air. This could be disadvantageous in hot climates unless additional energy is expended on cooling the desiccant. Alternatively, a higher concentration desiccant solution can be used but this also has a cost.
• Large capillaries give [illegible]er cap[illegible]y at hig[illegible]	• Higher concentration allows air to be dried to a greater degree.
• can combine adsorben[illegible] satisfa[illegible]y operation across a wide range of conditions	Maximize water molecule absorption by: • increasing surface area exposed to air • increasing contact time.
Form: High surface area to mass ratio (e.g. >4600 m^2/g) like a rigid Sponge.	LiCl with air at 90% RH, equilibrium
Function: • water condensed into desiccant capillaries-moisture attracted by electrical field at desiccant surface, force field not uniform. Single water molecules held within crystalline structure of desiccant material • complete surface covered with water molecules • vapor condenses into first water layer- capillaries are filled throughout desiccant	26 water molecules/ LiCl molecule or 1000% of dry mass. Achieve this by: – spraying desiccant into air (like cooling tower) – rotating extended surface.
Operating life up to 100,000 h. Loss of capacity by contaminants, clogging by dust and organic vapors, hydrothermal stress (due to expansion/contraction).	Operating life up to 100,000 h. Loss of capacity by contaminants reacting chemically with the desiccant solution causing its properties to change.

not change chemically or physically when water vapor is added are called adsorbents. In contrast, absorbents undergo chemical or physical changes when they absorb water. Usually, adsorbents are solids while absorbents are liquids. Some patent documents predicted that daily fresh water production from desiccant AWVP technology would be millions of *L*. Two types of desiccant technology are compared in Table 6. Solid desiccant technology uses materials having large internal surface area per unit mass, for example, 4600 $m^2\,g^{-1}$ (ASHRAE) [9]. Water vapor molecules are attracted to the desiccant surface electrical field and condense inside capillaries.

Heaters force collected water molecules out of the adsorbent. Heated, moisture rich air flows past refrigerated surfaces to condense water vapor. The following conclusions are summarized from different researches [5]:

1. The suggested hydrated salts coating various inert carriers are effective water vapor adsorbents.
2. Desiccant by itself is less effective as a moisture getter than when supported on a carrier. They found adsorption rate increases linearly with relative humidity.
3. Actual atmospheric water recovery, using a sand/calcium chloride mixture, was 15.5 $m^3\,day^{-1}\,ha^{-1}$.
4. using Silica gel as adsorbent.
5. Properties of various adsorbents are listed in Table 7.

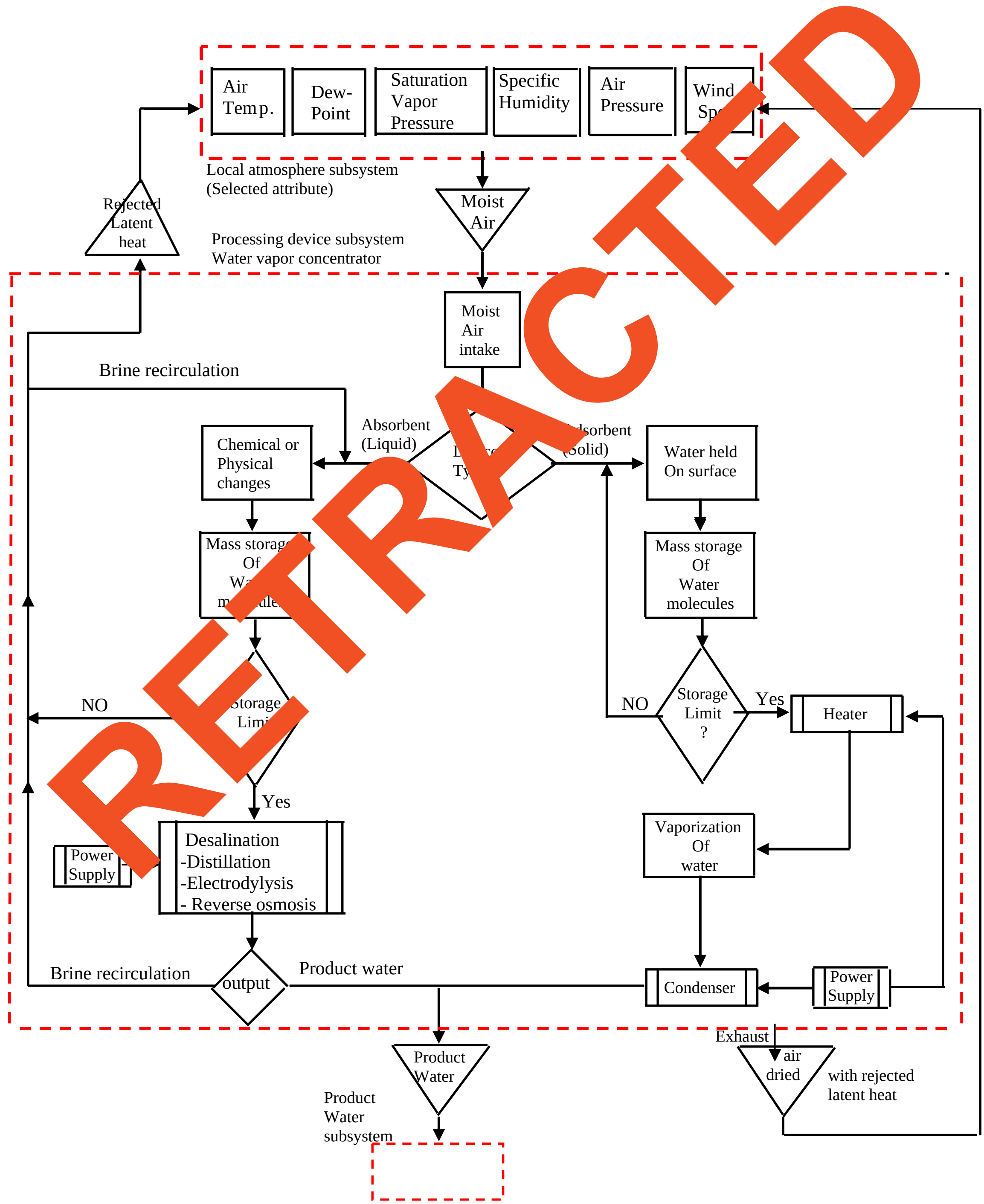


Fig. 4. Design type 2: desiccant (liquid or solid) systems for atmospheric water vapor processing presented as an energy and mass cascade [6].

Liquid desiccants are a different case. Water vapor is attracted by the vapor pressure gradient and changes phase upon absorption by the liquid. Some designs of air water vapor processors (AWVP) are using an 80% solution of lithium chloride in water as absorbent. While the other ones are using triethylene glycol as liquid desiccant and solar distillation techniques for desorption. Sorption characteristics of adsorbents and absorbents are ranked in Table (8) [6].

The energy and mass cascade for desiccant based strategies is shown in Fig. 4. A three-step desiccant cycle applies to both liquid and solid sorbents (Table 9). Performance of desiccant dehumidifiers is expressed in AWVP terms in Table 10) [6].

2.2.1. *Absorption-regeneration cycle (using liquid desiccant) [7]*

One of the first works dealing with water extraction from atmospheric air was published in Russia [7]. An apparatus consisting of a system of vertical and inclined channels in the earth to collect water from atmospheric air by cooling moist air to a temperature lower than its dew point has been proposed.

Description and analysis of the theoretical cycle for absorption of water vapor from air with subsequent re-generation, by heating is presented in Hamed et al. [7]. A theoretical limit for the maximum possible amount of water which can be collected from air using the desiccant through the absorption regeneration cycle at certain operating conditions of ambient parameters, heat to be added to the desiccant during regeneration and maximum available heating temperature could be evaluated through the analysis of this cycle. The absorption regeneration cycle, which can be applied for the production of water from atmospheric air, is shown in Fig. 5. The theoretical cycle is plotted on the vapor pressure-concentration diagram for the operating absorbent and consists of four thermal processes which are given in Table 6.

This cycle can be applied in desiccant systems with different configurations and different heat sources. As the purpose of this cycle is to produce water from air and the input energy to the system is the heat added during the regeneration process, then the efficiency of the cycle can be defined as the ratio of heat added to regenerated vapor to the total heat added.

Theoretical analysis showed that, strong and weak solution concentration limits play a decisive role in the value of cycle efficiency. However, a modified cycle is described and analyzed by Sultan [8]. In this modified cycle, the practical considerations were taken into account.

A system for the production of water from atmospheric air by absorption was proposed, using Ethylene glycol as a liquid desiccant with subsequent recovery in a solar still [7]. The effects of temperature and humidity on the recovered water were studied and the results presented in the form of a composite psychometric chart, but the paper does not provide any information about the mass of recovered water. A non-conventional system to collect water from air based on an adsorption–desorption process using a solid desiccant was constructed [7]. The study also discussed the feasibility of the application of air conditioning systems for collecting water from moist air by cooling it to a temperature lower than the dew point. A typical S-shaped composite material for absorption of moisture from atmospheric air with subsequent regeneration using solar energy was used [7]. Hamed et al. [7] tested two methods to extract water from atmospheric air using solar energy. The first method was based on cooling moist air to a temperature lower than the air dew point using solar absorption cooling system. The second method was based on the absorption of moisture from atmospheric air during the night using calcium chloride solution as a liquid desiccant, with sub-sequent recovery of absorbed water during the day. As a result of this study, the second method was recommended as a most suitable application of solar energy for water recovery from air.

Table 9
Adsorbent classes and properties [6].

Class	Properties
Silica gels	Low cost, easy to customize for selective adsorption. Physically, these range from fine powder to beads about 5 mm diameter.
Zeolites	Aluminosilicates, naturally occurring, open crystalline lattice functions as sieve.
Molecular sieves (synthetic zeolites)	Higher cost than natural zeolites but have uniform structure.
Activated aluminas	Manufactured for specific structural characteristics.
Carbons	High capacity for water molecules at $\phi=45–100\%$, easily adsorb organic solvents.
Synthetic polymers	Highest capacity of adsorbents. This is a relatively new technology with potential as a desiccant (e.g. polystyrenesulfonic acid sodium salt, PSSASS).

Table 10
Desiccant cycle summary with reference to AWVP [6].

Stage	Process	
1	Water sorption	Vapor pressure gradient causes water molecules to leave air stream and enter desiccant. Latent heat is converted to sensible heat, warming the air stream.
2	Desiccant reactivation or regeneration	Vapor pressure gradient between air and desiccant has declined to zero. It is time to drive the moisture out of the desiccant by heating it to as high as 120 °C. This reverses the vapor pressure gradient so that water molecules leave the desiccant and enter the lower vapor pressure scavenging air stream that picks up the water molecules. In an AWVP device, especially if using solid desiccants, this air stream must be cooled later to cause the water vapor to condense so that liquid water can be collected and stored (Fig. 4). For a liquid desiccant device it is possible that the water could be separated from the brine by desalination techniques. Regeneration energy = energy required to raise desiccant temperature so that vapor pressure gradient is reversed + energy needed to evaporate water in desiccant + energy associated with desorption of water from the desiccant.
3	Desiccant cooling	Cooling of the desiccant itself must occur so that the original water vapor gradient is reestablished to begin a new cycle of water molecule collection at Stage 1. Typical cooling might be from 120 °C to 10 °C.Cooling energy = f (desiccant mass, difference between maximum reactivation temperature and Stage 1 starting temperature).

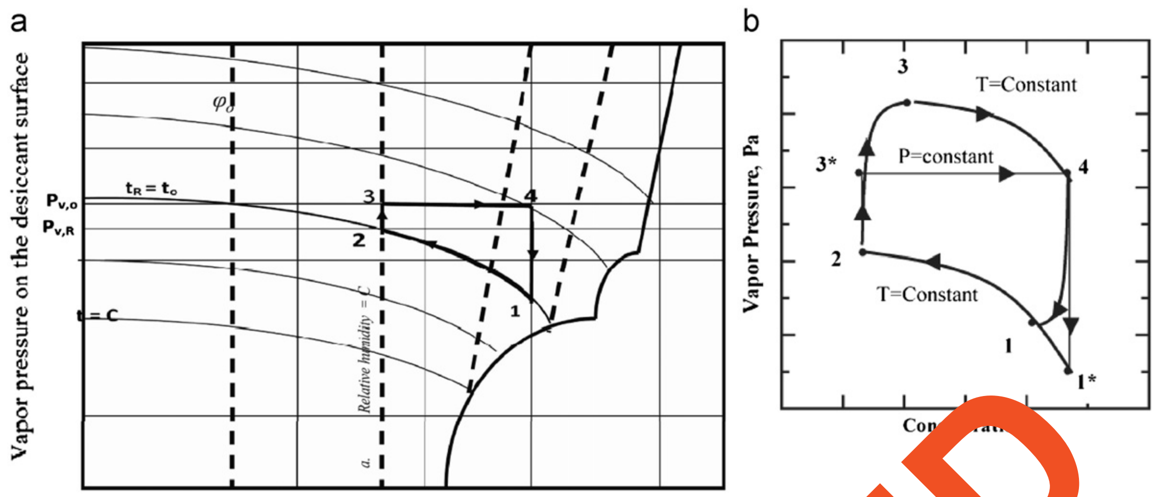


Fig. 5. (a): Absorption-regeneration cycle [7]. (b) Absorption-regeneration improved cycle [8].

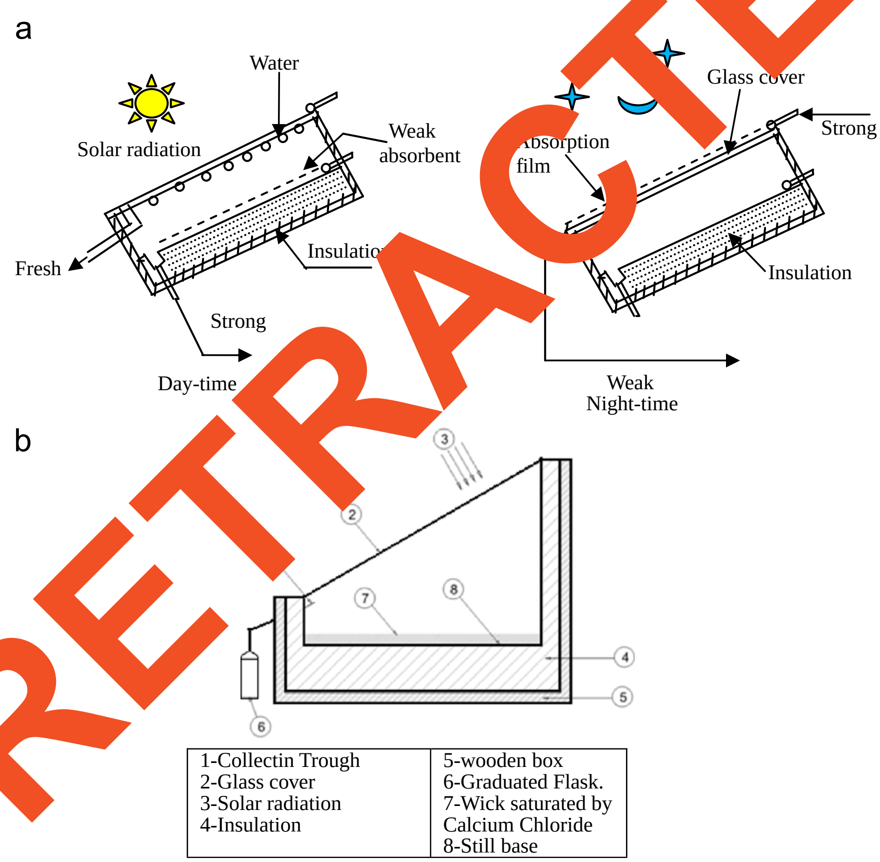


Fig. 6. (a): The system proposed by Abualhamayel and Gandhidasan [11]. (b): The system proposed by The system proposed by Gad et al. [12] 1-Collection Trough, 2-Glass cover, 3-Solar radiation, 4-Insulation, 5-wooden box, 6-Graduated Flask. 7-Wick saturated by Calcium Chloride, 8-Still base.

Abualhamayel and Gandhidasan [11] proposed the system shown in Fig. 6 for water recovery from air. The system consists of a flat, blackened, tilted surface and is covered by a single glazing with an air gap of about 45 cm. The bottom of the unit is well insulated. At night, the strong absorbent flows down as a thin film over the glass cover in contact with the ambient air. If the vapor pressure of the strong desiccant is less than the vapor pressure of water in the atmospheric air, mass transfer takes place from the atmosphere to the absorbent. Due to absorption of moisture from the ambient air during the night, the absorbent be-comes diluted. The water-rich absorbent must be heated during the day to recover the water from the weak absorbent. Therefore, during the day, the weak desiccant flows down as a thin film over the absorber surface. The weak absorbent is heated by solar energy, and the water that evaporates from the solution rises to the glass cover by convection where it is condensed on the underside of the glass cover and the absorbent leaving the unit becomes strong. The performance of the unit at night depends on

the potential for mass transfer, which is the difference in water vapor pressure between the ambient air and desiccant.

The performance of a desiccant/collector system with a thick corrugated layer of blackened cloth to absorb water vapor at night from atmospheric air with subsequent regeneration during the day, using solar energy, was reported by Gad et al. [12]. Fig. 7 shows a schematic diagram of the experimental apparatus. It consists mainly of three parts: a flat plate collector with a movable glass cover, a corrugated bed and an air-cooled condenser consisting of two parallel flat plates. Actual recorded results show that the solar operated system can provide about 1.5 l of fresh water per square meter per day.

The need for economical realization of solar-desiccant systems for water production in arid areas is of great importance. Moreover, the inconvenience and relatively high cost of the desiccant bed limits the utilization of such units in large scale. In desert regions, mixing a sandy layer of the ground surface with desiccant is a promising method to minimize the cost of the vapor absorption bed was proposed [7]. The sandy layer impregnated with desiccant is subjected to ambient atmosphere to absorb water vapor in the night. During the sunshine period, the layer is covered with a greenhouse where desiccant is regenerated and water vapor is condensed on the transparent surface of the greenhouse or any other cold surface. Prediction of the absorption cycle performance requires knowledge of the percentage approach to saturation. In view of the design parameters of the absorption bed, the desiccant to sand mass ratio is an important factor affecting the rate of absorption and consequently the rate of water production. This issue was investigated experimentally [7]. Extracting water from air by using sandy bed solar collector system is explored by Kabeel [13]. The system is studied theoretically and experimentally to evaluate the performance of the sandy bed impregnated with 30% concentration calcium chloride to produce water from moist air. It is reported that the system can provide up to about 1.2 l fresh water per square meter of glass cover per day in the climatic conditions of Tanta city, Egypt which is mostly humid.

The application of solar concentrator for fresh water production from the atmospheric air is reported also [14]. The extraction of water from air (EWA) patented technology, based on the extraction of air humidity into water stream, was developed for large-scale water supply, up to 1000 m3/d. Such as desalination, using the unlimited free source of salty water, the EWA technology makes use of air humidity. The EWA technology could serve as an alternative solution for water supply, where neither salty water, nor infrastructure is available. The EWA technology extracts the air humidity by a three stage process: absorption of humidity on a solid desiccant, desorption of the water to vapor at moderate heat (65–85 °C) and condensation with passive condenser connected to a heat pump. The moderate heating enables the utilization of environmentally friendly and low cost heat energy, such as solar or waste heat. The combination of moderate heat, passive condenser and heat pump allows producing water with low energy consumption of 100–150 kcal/1. The EWA technology is based on a multi-cycle regime, each cycle lasts about 90 min with absorption/desorption ratio of 2:1. The EWA technology is made of modular cassettes enabling a design of a device for any required capacity up to 1,000 m^3/d. The EWA technology could be operated at ambient temperature range between 5 and 45 °C and at relative humidity of 20% and more, while at relative humidity of 60% the system achieves its maximal capacity. The EWA technology may provide a reasonable solution

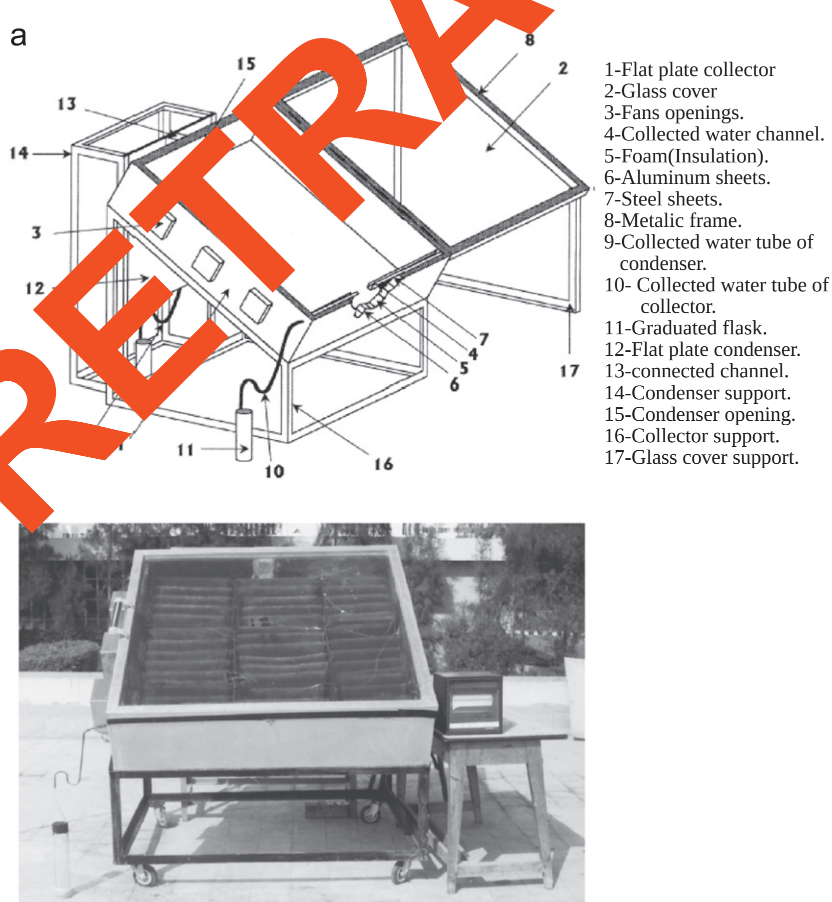


Fig. 7. (a) Experimental apparatus made by Gad et al. [12] (b): General view of the experimental apparatus [12].

for water supply in dry regions, including South Mediterranean countries, as well as countries suffering from polluted water, including tropical countries, and far from the seashores where long-pipe systems are not available, the EWA technology would present the excellent solution for fresh water [14,15].

The capability of the glass pyramid shape with a multi-shelf solar system to extract water from humid air is explored in [7]. Two pyramids were used with different types of beds on the shelves. The beds are saturated with 30% concentrated calcium chloride solution. The pyramid sides were opened at night to allow the bed saturated with moist air and closed during the day to extract the moisture from the bed by solar radiation. The bed in the first pyramid was made of saw wood while it is made of cloth in the second pyramid with the same dimensions. The system was experimentally investigated at different climatic conditions to study the effect of pyramid shape on the absorption and regeneration processes. Preliminary results have shown that the cloths bed absorbs more solution (9 kg) as compared to the saw wood bed (8 kg). Adopting this approach, the system produces about 2.5 l/(day m^2).

2.3. Type-3: inducing and controlling convection in a structure

Another way of lowering air temperature below the dew point is to cause air parcels to expand, transforming a portion of their energy into work, cooling air to extract liquid water.

Convection based water vapor processors were championed by Roland and Wahlgre [6]. Fig. 8 shows the energy and mass cascade. These processors contain a convection cell of moist air inside a vertical tube or tower wh[illegible] extend 100 or 1000 of

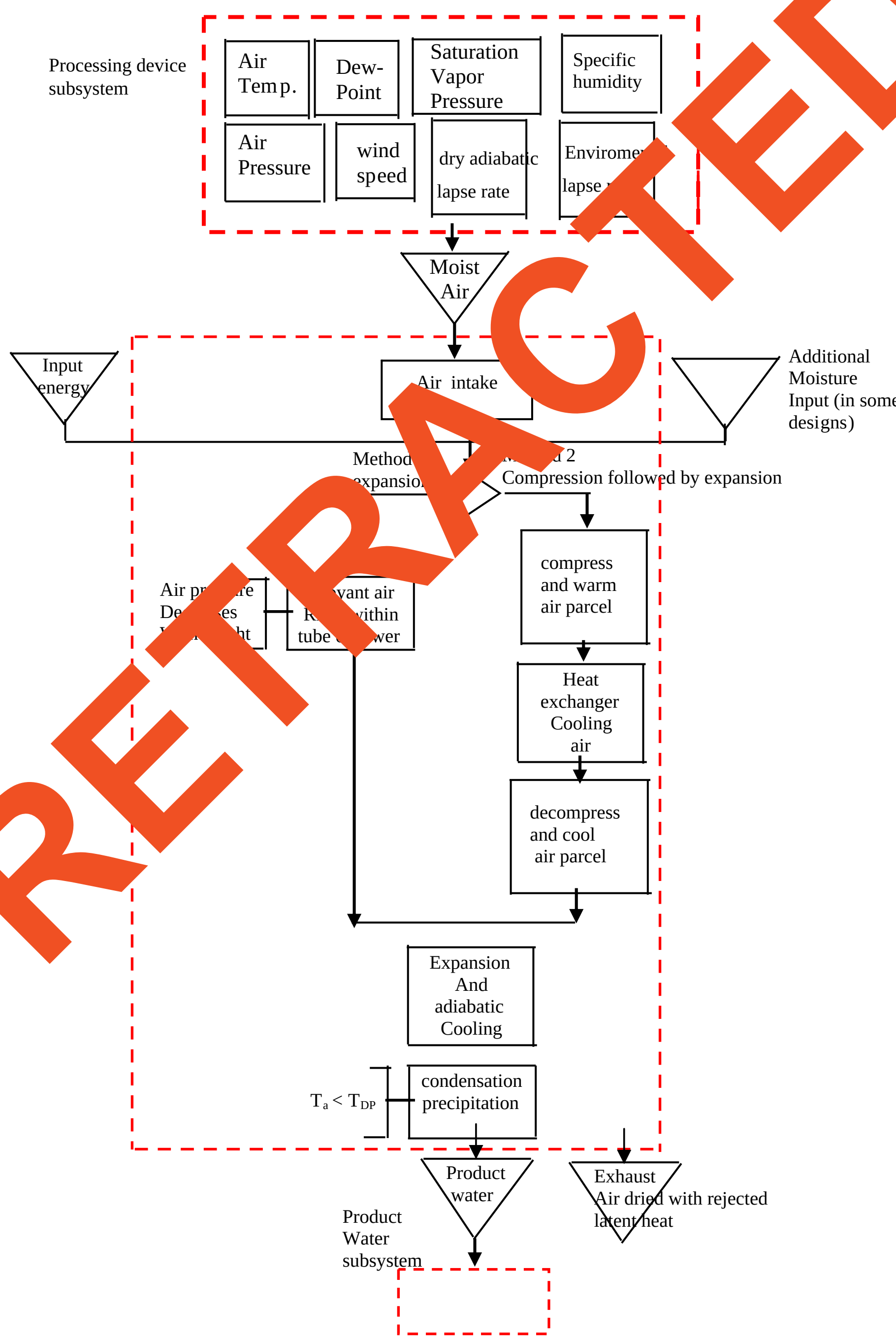


Fig. 8. Design type 3: convection process for AWVP viewed as an energy and mass cascade [6].

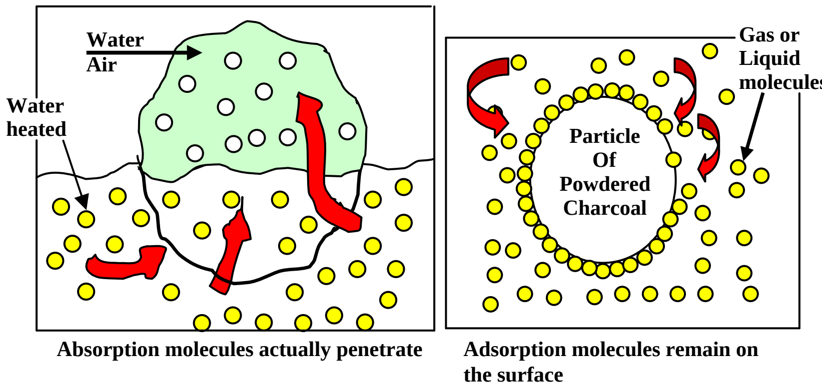


Fig. 9. Working principle of adsorption and absorption processes [6] (LiCl), (CaCl2), (LiBr).

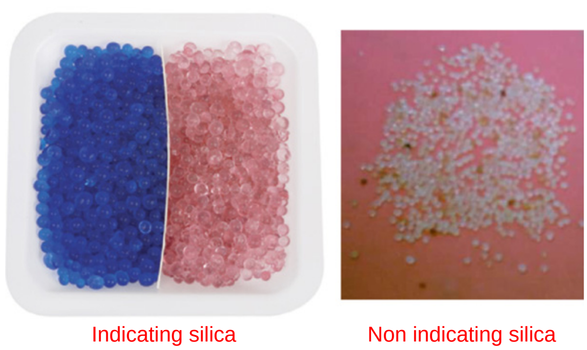


Fig. 10. Photo for indicating and non indicating silica.

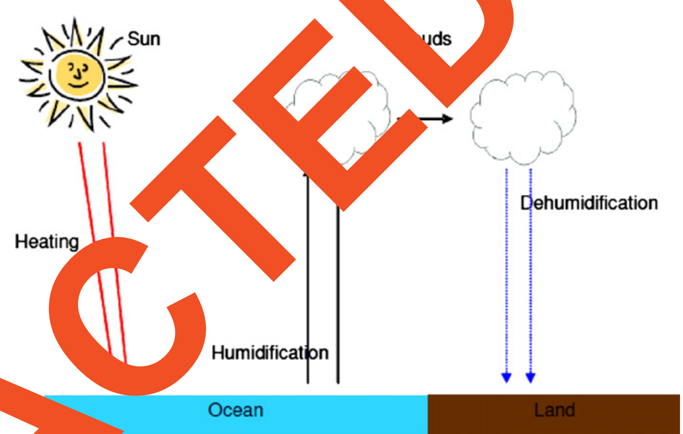


Fig. 11. Rain cycle [10].

meters up into the atmosphere (structural engineering of these designs is a challenge). Moist adiabatic cooling occurs as the cell expands in volume when forced upwards into a zone of lower air pressure by induced convection. Condensation and precipitation occur within the column when the temperature of the convection cell drops below the dew point.

3. AWVP some details and useful comparisons:

3.1. Sorption systems (adsorption and absorption processes using desiccants)

Desiccants acting as water vapor concentrators extract water vapor from air by establishing a vapor pressure gradient causing flow of water molecules toward the desiccant surface. Desiccants that do not change chemically or physically when water vapor is added are called adsorbents. In contrast, absorbents undergo chemical or physical changes when they absorb water. Usually, adsorbents are solids while absorbents are liquids. Some patent documents predicted that daily fresh water production from desiccant AWVP technology would be millions of litre.

Two types of desiccant technology are shown in Fig. 9 and compared in Table 8. Solid desiccant technology uses materials having large internal surface area per unit mass,. Water vapor molecules are attracted to the desiccant surface electrical field and condense inside capillaries

3.2. Demystifying silica gel

- Silica gel desiccant is widely used in industrial drying processes. It is a hard, granular, very porous product made from gel precipitated by acid treatment of sodium silicate solution.
- Silica gel comes from manufacturers as white (Non indicating) or blue (Indicating) type as shown in Fig. 10

3.3. Desiccant applications

Desiccants can dry either liquids or gases, including ambient air, and are used in many air conditioning applications, particularly when

- The latent heat load is large in comparison to the sensible heat load.
- The cost of energy to regenerate the desiccant is low compared to the cost of energy to dehumidify the air by chilling it below its dew point.

The ideal adsorbent should be

- Insoluble
- Macroporous
- Mechanically and chemically stable
- Hydrophilic
- Resistant to microbial and enzymatic attack

4. Humidification–dehumidification (H–DH) desalination technology [10]

Nature uses solar energy to desalinate ocean water by means of the rain cycle (Fig. 11). In the rain cycle, sea water gets heated

(by solar irradiation) and humidifies the air which acts as a carrier gas. Then the humidified air rises and forms clouds. Eventually, the clouds 'dehumidify' as rain. The man-made version of this cycle is called the humidification–dehumidification desalination (H–DH) cycle.

The H–DH cycle has received much attention in recent years and many researchers have investigated the intricacies of this technology. It should be noted here that the predecessor of the HDH cycle is the simple solar still. Several researchers have reviewed the numerous works on the solar still and hence, this paper will not discuss that technology. However, it is important to understand the disadvantages of the solar still concept.

The most prohibitive drawback of a solar still is its low efficiency (Gained-output ratio less than 0.5) which is primarily the result of the immediate loss of the latent heat of condensation through the glass cover of the still. Some designs recover and reuse the heat of condensation, increasing the efficiency of the still. These designs (called multi-effect stills) achieve some increase in the efficiency of the still but the overall performance is still relatively low. The main drawback of the solar still is that the various functional processes (solar absorption, evaporation, condensation, and heat recovery) all occur within a single component. By separating these functions into distinct components, thermal inefficiencies may be reduced and overall performance improves. This separation of functions is the essential characteristic of the H–DH system. For example, the recovery of the latent heat of condensation, in the H–DH process, is affected in a separate heat exchanger (the dehumidifier) where in the seawater, for example, can be preheated. The module for solar collection can be optimized almost independently of the humidification or condensation component. The HDH process, thus, promises higher productivity due to the separation of the basic processes.

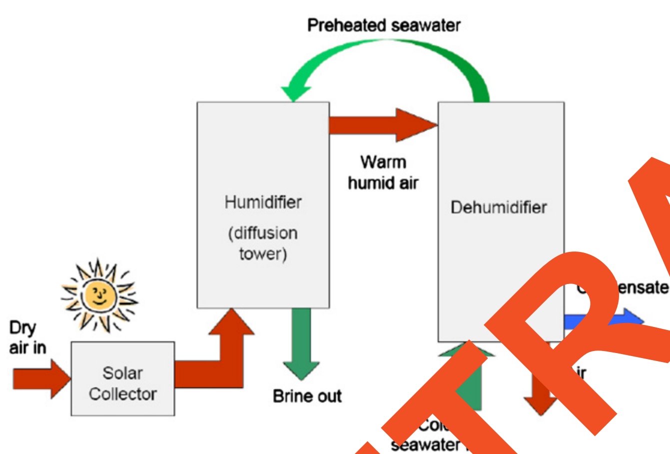


Fig. 12. A simple humidification dehumidification (H–DH) process. [10].

The simplest form of the H–DH process is illustrated in Fig. 12. The process constitutes of three subsystems: (a) the air and/or the water heater, which can use various sources of heat like solar, thermal, geothermal or combinations of these; (b) the humidifier or the evaporator and (c) the dehumidifier or the condenser.

4.1. Classification of H/DH systems

H–DH systems are classified under three broad categories. One is based on the form of energy used such as solar, thermal, geothermal, or hybrid systems. This classification brings out the most promising merit of the H–DH concept, which is the promise of water production by use of low grade energy, especially from renewable sources.

The second classification of H–DH processes is based on the cycle configuration shown in Fig. 13. As the name suggests, a closed-water open-air (CWOA) cycle is one in which the air is heated, humidified and partially dehumidified and let out in an open cycle as opposed to a closed air cycle wherein the air is circulated in a closed loop between the humidifier and the dehumidifier. The air in these systems can be circulated by either natural convection or mechanical blowers.

It is of pivotal importance to understand the relative technical advantages of each of these cycles and choose the one that is best in terms of efficiency and cost of water production. In the published literature, not much attention has been paid to optimization of the cycle itself as compared to the optimization of the three sub-systems. Furthermore, a few investigators have studied the cost of the H–DH cycles and found that the cost of water production is high [10].

The third classification of the H–DH systems is based on the type of heating used—water or air heating systems. The performance of

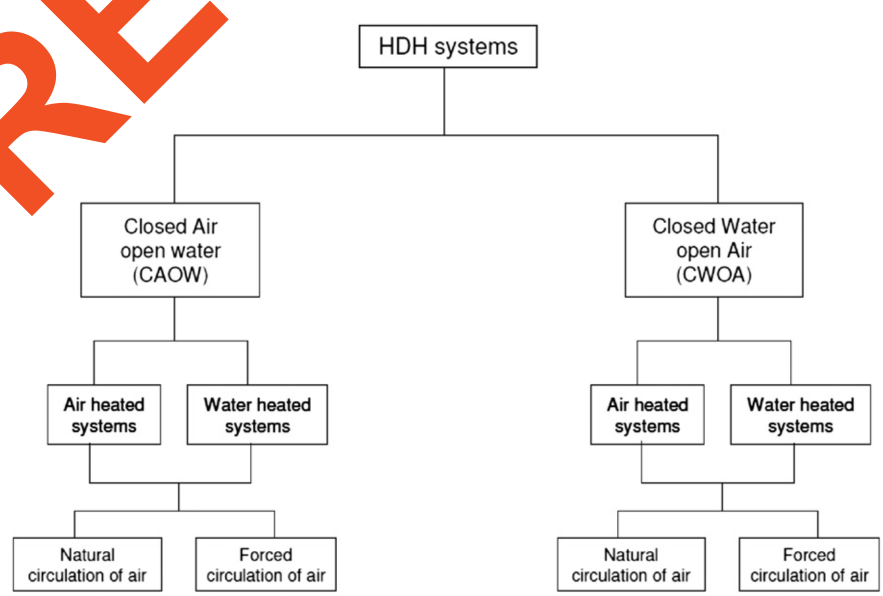


Fig. 13. Classification of typical H–DH processes (based on cycle configuration [10].

the system depends greatly on whether the air or water is heated. While there are many decades of experience and wisdom on solar water heating devices, relatively little work has been done on the solar collectors for air heating. Considering their importance to the overall H–DH system performance, solar air heating devices are also reviewed in this paper.

4.2. Review of systems in literature

As a first step for understanding different works in literature the following performance parameters are defined.

(1) *Gained-Output-Ratio* (*GOR*): is the ratio of the latent heat of evaporation of the distillate produced to the total heat input absorbed by the solar collector(s). This parameter is, essentially, the efficiency of water production and an index of the amount of the heat recovery effected in the system. This parameter does not account for the solar collector efficiency as it just takes into account the heat obtained in the solar collector. For the HDH systems to have thermal performance comparable to MSF or MED, a GOR of at least 8 (corresponding to energy consumption rates of ~300 kJ/kg) should be achieved.
(2) *Specific water production*: This is the amount of water produced per m^2 of solar collector area per day. This parameter is an index of the solar energy efficiency of the HDH cycle. This parameter is of great importance as the majority of the capital cost of the HDH system is the solar collector cost: 40–45% for air heated systems and 20–35% for water heated systems [10].
(3) *Recovery ratio* (*RR*): is the ratio of the amount of water produced per kg of feed. This parameter is also called the extraction efficiency. This is, generally, found to be much lower for the HDH system than conventional systems. The advantage of a low recovery ratio is that complex brine pre-treatment process or brine disposal processes may not be required for this system.
(4) *Energy reuse factor* (f): is the ratio of energy recovered from the heated fluid to the energy supplied to the heated fluid [10]. This is another index of heat recovery of the system.

4.3. Closed-air open-water (CAOW) water heated systems

A typical CAOW system is shown in Fig. 14. The humidifier is irrigated with hot water and the air stream is heated and humidified using the energy from the hot water stream. This process on the psychometric chart is represented by the line 1–2 (Fig. 15). The humidified air goes to the dehumidifier and is cooled in a compact heat exchanger using sea water as the coolant. The seawater gets preheated in the process and is further heated in a solar collector (Q_{in} indicated in Fig. 14 is the heat absorbed in the solar collector by the seawater as used in the calculation of GOR) before it irrigates the humidifier. The dehumidified air stream from the dehumidifier is then circulated back to the humidifier. This process on the psychometric chart is represented by the line 2–1 (Fig. 15).

There are several works in the literature on this type of cycle. Some common conclusions can be drawn from these works. Almost all the investigators have observed that the performance is maximized at a particular value of the water flow rate. There also is an almost unanimous consensus that natural circulation of air yields better efficiency than forced circulation of air for the closed air water heated cycle. However, it is not possible to ascertain the exact advantage in performance (for natural circulation) from the data available in literature. Using the data given in these papers, GOR and specific water production were calculated

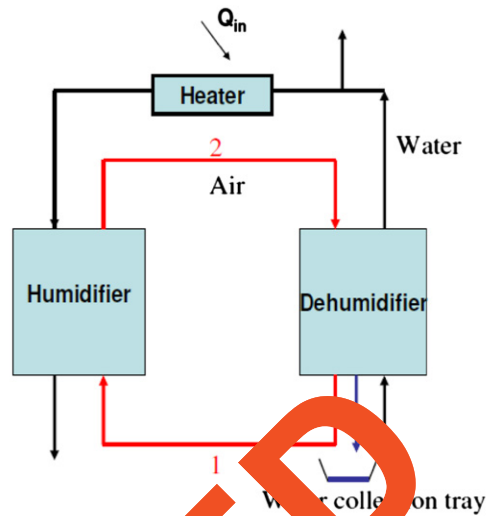


Fig. 14. A typical water heated CAOW H–DH process [10].

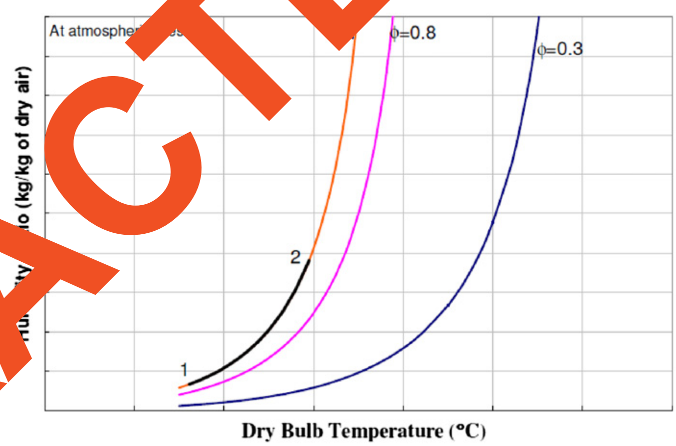


Fig. 15. Water heated CAOW H–DH process on psychometric chart [10].

by the present authors (Fig. 16). The specific water production was found to be between 4 and 12 $kg/m^2 \cdot day$ and the GOR varied between 1.2 and 4.5. These values of GOR translate into energy consumption rates from 140 kWh/m3 to 550 kWh/m3. This is higher than that for conventional technologies like MSF or RO. RO plants, which are the most energy efficient, consume about 4–10 kWh/m^3. However, one should keep in mind that the energy supplied is 'free' for these solar HDH systems: GOR for a solar-driven cycle is a measure of thermal performance but it is less directly a measure of water cost.

The low value of GOR achieved by Ben Bacha et al. [16] was because they did not recover the latent heat of condensation. Instead, they used separate cooling water from a well to dehumidify the air. The higher value of GOR achieved by Müller-Holst et al. [17] was because of high heat recovery. These results tell us the importance of enhanced latent heat recovery to minimize the energy consumption and the cost of CAOW water heated system. Further, Wang et al. [39] also reported that the cost can be brought down by ~50% if a heat storage unit is used in the H–DH system.

4.4. Multi effect closed-air open-water (CAOW) water heated system

To enhance heat recovery, the concept of multi-effect H–DH was proposed [10]. Figs. 17 and 18 illustrate an example of this

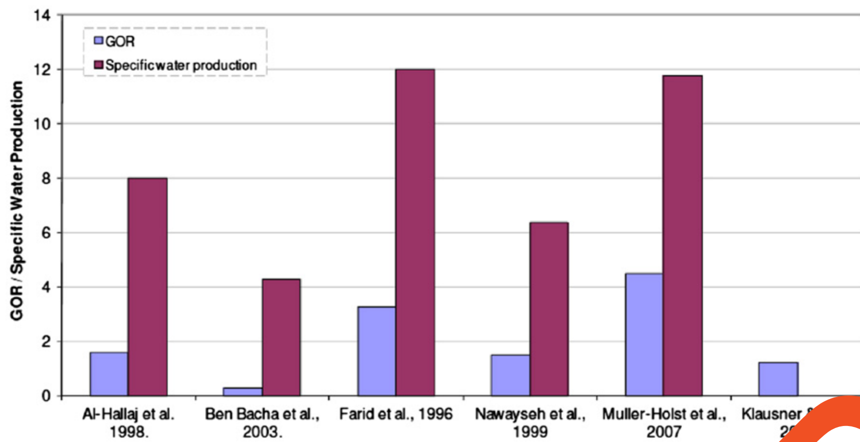


Fig. 16. Performance parameters for various works on single & multi effect water heated CAOW H–DH cycle [10].

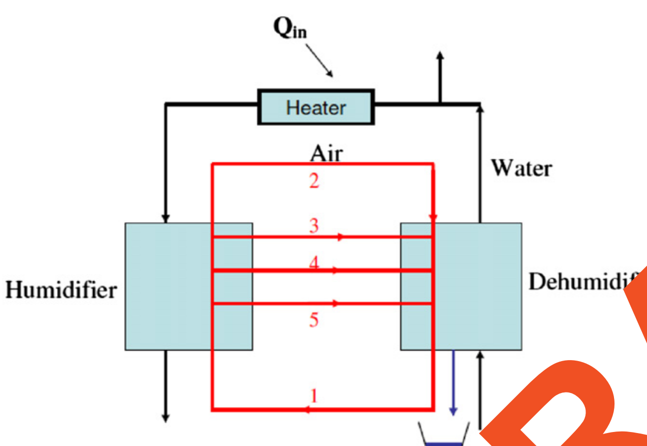


Fig. 17. Multi-effect water heated CAOW H–DH cycle [10].

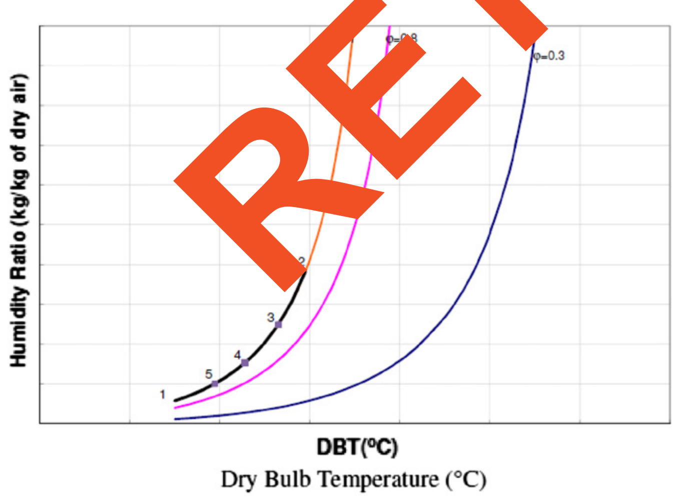


Fig. 18. Multi-effect water heated CAOW H–DH process on psychometric chart [10].

system. Air from the humidifier is extracted at various points and supplied to the dehumidifier at corresponding points. This enables continuous temperature stratification resulting in small temperature gap to keep the process running. This in turn results in a higher heat recovery from the dehumidifier.

In fact, most of the energy needed for the humidification process is regained from the dehumidifier bringing down the energy demand to a reported value of 120 kWh/m^3. This system is being commercially produced and marketed by a commercial water management company, Tinox GmbH. This is, perhaps, the first instance in which the H–DH concept has been commercialized.

4.5. *Closed-water open-air (CWOA) water heated systems*

A typical CWOA system is shown in Fig. 19. In this system the air is heated and humidified in the humidifier using the hot water from the solar collector and then is dehumidified using outlet water from the humidifier. The water, after being pre-heated in the dehumidifier, enters the solar collector, thus working in a closed loop. The dehumidified air is released to ambient. The humidification process is shown in the psychometric chart (Fig. 20) by line 1–2. Air entering at ambient conditions is saturated to a point 2 (in the humidifier) and then the saturated air follows a line 2–3 (in the dehumidifier). The air is dehumidified along the saturation line. A relatively small number of works in literature consider this type of cycle. The important features of the system and main observations from these studies were studied.

One disadvantage of the CWOA is that when the humidification process does not cool the water sufficiently the coolant water temperature to the inlet of the dehumidifier goes up. This limits the dehumidification of the humid air resulting in a reduced water production compared to the open water cycle. However, when efficient humidifiers at optimal operating conditions are used, the water may be potentially cooled to temperature below the ambient temperature (up to the limit of the ambient wet-bulb temperature). Under those conditions, the closed water system is more productive than the open water system [10].

4.6. *Closed-air open-water (CAOW) air heated systems*

Another class of H–DH systems which has attracted much interest is the air heated system. These systems are of two types—single and multi-stage systems. Fig. 21 is a schematic diagram of a single stage system. The air is heated in a solar collector to a temperature of 80–90 °C and sent to a humidifier. This heating process is represented by the constant humidity line 1–2 in the psychometric chart (Fig. 22). In the humidifier, the air

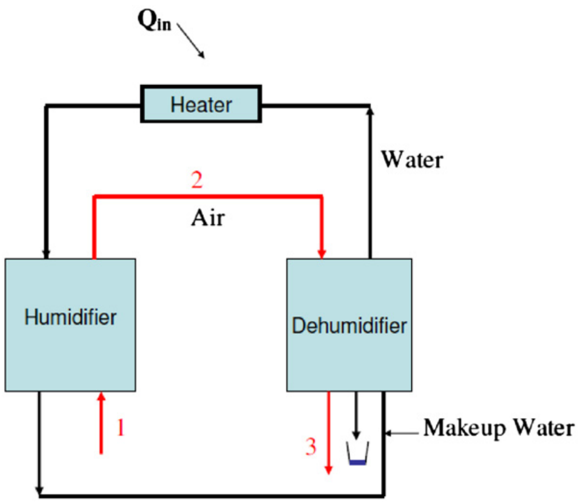


Fig. 19. A typical water heated CWOA H–DH process [10].

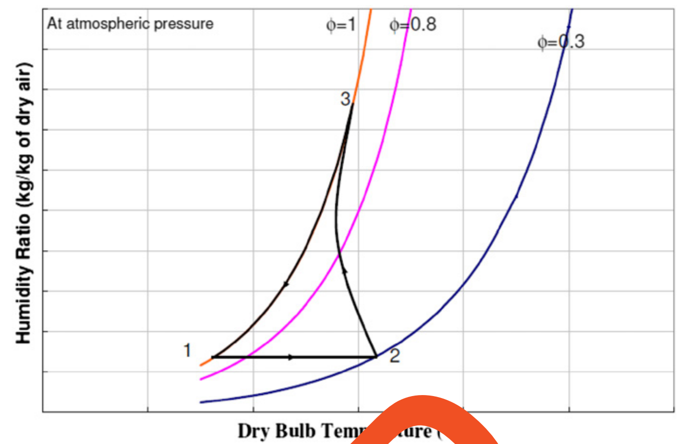


Fig. 22. Air heated CAOW H–DH process on psychometric chart [10].

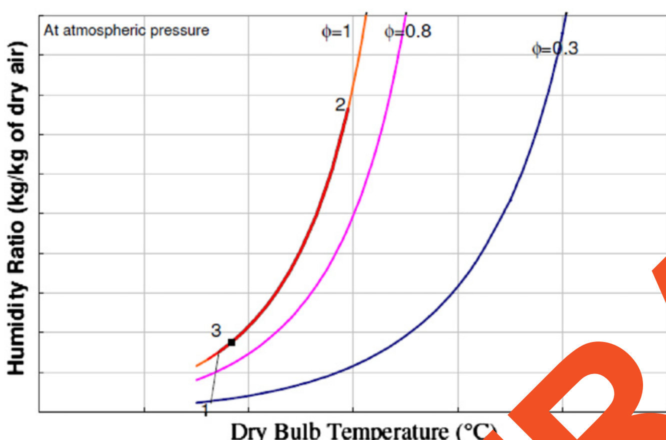


Fig. 20. Water heated CWOA H–DH process on psychrometric chart [10].

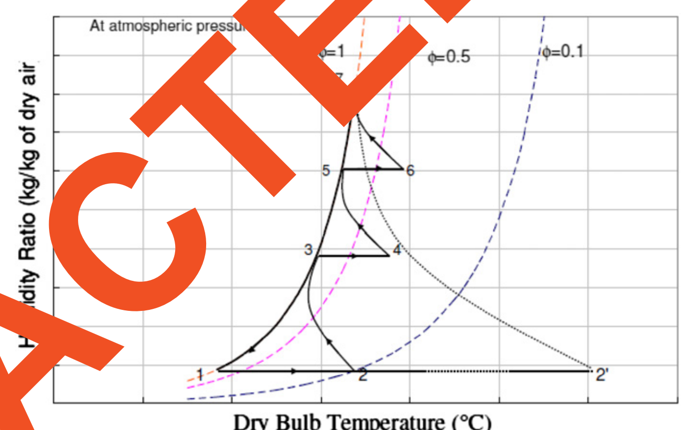


Fig. 23. Multistage air heated CWOA H–DH process on psychometric chart [10].

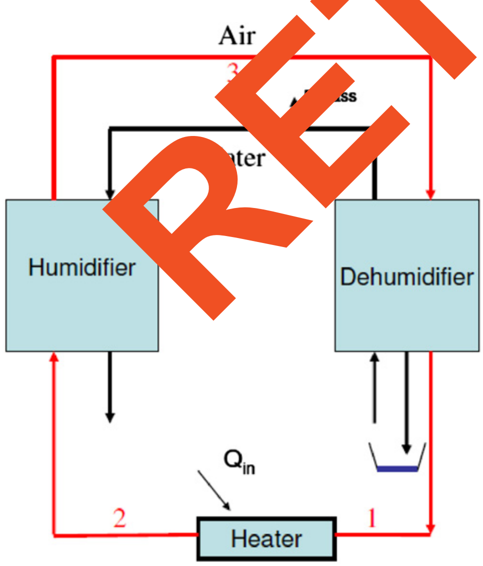


Fig. 21. A typical air heated CAOW H–DH process [10].

is cooled and saturated. This process is represented by the line 2–3. It is then dehumidified and cooled in the process 3–1 represented on the saturation line. A major disadvantage of this cycle is that the absolute humidity of air that can be achieved at these temperatures is very low (< 6% by weight). This impedes the water productivity of the cycle.

Chafik [18] reported a method to address this problem. He used a multistage heating and humidification cycle as shown in Fig. 23. The air after getting heated in the solar collector (line 1–2) and humidified in the evaporator (line 2–3) is fed to another solar collector for further heating (line 3–4) and then to another humidifier (line 4–5) to attain a higher value of absolute humidity. Many such stages can be arranged to attain absolute humidity values of 15% and beyond. Point 2′two dash) in the figure represents the high temperature that has to be reached in a single stage cycle to attain the same humidity as a 3 stage cycle. This higher temperature has substantial disadvantages for the solar collectors. However, from an energy efficiency point of view, there is not much of an advantage to multi-staging, as the higher water production comes with a higher energy input as compared to single stage systems. Also, from the various studies in literature, we observe that the air-heated systems have higher energy consumption than water heated systems. This is because air heats up the water in the humidifier and this energy is not subsequently recovered from the water, unlike in the water-heated cycle in which the water stream is cooled in the humidifier.

It should be noted that the CAOW air-heated systems have not been studied so far in literature and hence will not be dealt with in this paper.

5. Review of component designs

5.1. Solar air heater designs

Solar water heating systems have been studied and used widely for many decades [10], and hence extensive knowledge exists on the design of these systems. Solar air heating, in contrast, has not been studied extensively. Considering the importance of solar air heaters to the overall performance and cost of H–DH air-heating systems, they are reviewed in the current section. The heaters will be compared on the basis of their collection efficiencies (η), which is defined as the useful heat gain of the air stream (in watts) divided by the solar irradiation incident on the collector (also in watts), unless otherwise noted. This is the same as the instantaneous thermal efficiency test in the ASHRAE 93-2003 Standard [10].

$$\eta = \frac{\text{Hear gained by air}}{\text{Solar incident radiation}}$$

The collectors are typically flat plate with large airflow channels. Air flows over or under the absorber plate, and double-pass strategies are sometimes employed. Fig. 24 shows the layout of an air heating collector [10].

Solar air heating systems have been used since the World War II for home heating and low temperature applications. The Colorado solar house, built in 1959, utilized a heater that had stacked absorber plates in a panel with a single glazing to achieve a moderate temperature rise for home heating and cooling with 30% collection efficiency [10].

In the 1960s, solar energy was developed in India as a means of cheap energy for crop drying. Several designs that used both corrugated absorber surfaces as well as wire mesh packing on the absorber were tested [10]. This study also provided an overall efficiency that took into account the power to force air through the heater. It showed that corrugated surfaces performed better than those enhanced with wire mesh, achieving a maximum of 65% overall energy conversion efficiency. Polymer heaters were also considered glazing made of Tedlar, a polyvinylfluoride (PVF) film was tested [10]. It was found that, despite higher heat losses from the Tedlar, its improved transmittance compensated. A glass glazing closer to the absorber plate and Tedlar outer glazing worked better. This new material had the ability to increase efficiency and was also resistant to corrosion. Later two designs built in 1982 were tested and reported in the environment over a long period of time [10]. PVF offered better thermal performance than PVC. Both materials were subject to UV degradation, which resulted in shorter lifetimes, but they offered significant cost savings over glass and metals. Also, use of PVF materials, as well as polycarbonate (PC) in place of glass was made. Beginning with the 1973 oil crisis, more research was done on alternative energy, including solar air heaters. The use of multiple glazing and of passing air between the glazings was tested. The air passed under a corrugated absorber (parallel to the ribs) to be heated. Efficiency gains of [illegible] 15% were found when air was passed between the two glazings as it kept the outer glazing cooler and reduced convective losses. The vast majority of solar air heaters were also tested after this period. Many of these designs took up the issue of poor heat transfer associated with a laminar flow over a smooth absorber plate. Other designs used a perforated plate to create jets of air that pointed at the absorber. These designs have difficulties with large pressure drops and low overall efficiencies [10]. Another design shapes the collector into a dome with double glazing and air circulated on top of the absorber and under the second glazing. This design maximizes exposure to the sun, but also suffers greater losses because of its large area, parts of which may not be exposed to the sun and thus only adding to losses.

In the 1990s research continued, particularly in India where solar energy was being used for inexpensive low-grade heat. Designs that used packing materials above and below the absorber plate while passing air through the packing were compared. Efficiencies up to 70% were obtained when the air and packing were above the absorber plate. The study also compared different packing materials and found low porosity and small particle diameter packing worked best. A wire matrix air heater, where air was flowing through the matrix was evaluated. The heater was intended for a crop drying application.

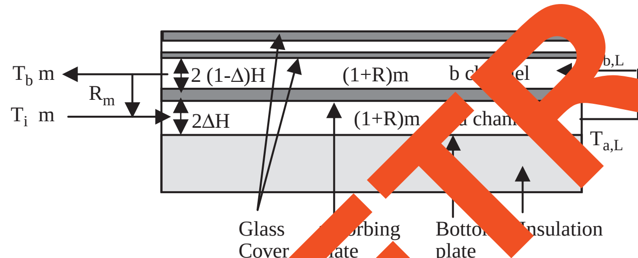


Fig. 24. Flow through a solar air collector [10].

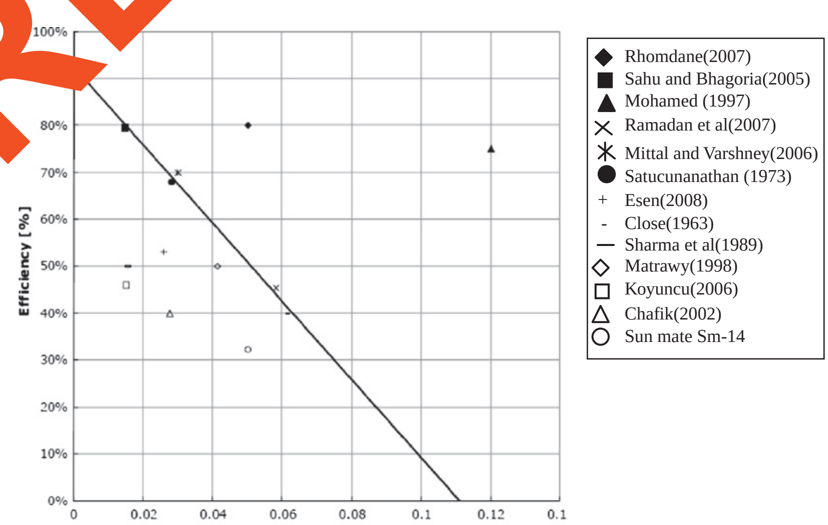


Fig. 25. Performance comparison of solar air heaters [10].

Modern air heater designs have focused mainly on improving convective heat transfer at the absorber. Using wire mesh as a packing material, with air flowing between the absorber the second glazing through the mesh was investigated, to achieve a collector efficiency of 70%. It was found that a packed bed of porous media improved heat transfer as well as pre-warming the air by first running it between two glazing plates. This also improved collector efficiency by reducing heat loss to the environment, and helped achieve an overall efficiency, which accounts for pumping losses for moving air through the collector of 75%. Several obstacles mounted on a flat plate to a plain flat plate were compared and found that short triangular shaped barriers improved heat transfer efficiency the most by breaking up the boundary layer and reducing dead zones in the collector. Small extensions from a metal plate to improve mixing of air on the plate were used. These extensions had the advantage of not increasing pressure drop like packed bed solar air heaters. The collector efficiency of a flat metal absorber plate was increased to 68% by running the air above and below the absorber plate [10]. The flow turns 180° to move back above the plate. This configuration increases pressure drop in the flow, but the paper does not specify how much. Also, an efficiency increase using double pass heating was reported.

Other attempts have been made to improve existing flat plate absorber with limited success. These designs sacrifice efficiency for simplicity. Several flat plate designs, with one ribbed plate design were compared, and several glazing configurations. The most efficient, at 45.8%, was flat black metal plate with a single polymer glazing, and air passing over the absorber. Fins below the absorber plate to enhance heat transfer to the air as it flowed under the absorber were used, but only achieved 50% collector efficiency. To date there are no commercial systems that utilize solar air heaters for solar desalination, only for home heating and crop drying. Most products have moderate temperature rise and are very expensive. Several of these products were rated by the Solar Collector and Certification Corporation, which gives efficiency data versus temperature rise normalized to solar radiation. Their efficiency data shows that for a temperature rise of 50 °C and a solar irradiation of 1 kW/m^2, which are representative values for a H–DH desalination application,, the best performing collector under these conditions is the Sunmate Sm-14, achieving only 32% efficiency [10].

5.1.1. Standardized comparison of designs

As with other heat exchangers, a solar air heater decreases in efficiency with a greater temperature rise due to increased loss. The most common way of showing solar air heater efficiency is to plot the efficiency versus normalized heat gain, which is the rise in air temperature divided by the solar irradiation flux. The normalized gain will decrease with increasing air mass flow rate. Fig. 25 shows the reported efficiencies of solar air heaters in the research literature as a function of normalized heat gain. The high efficiency commercial solar collector, the SunMate Sm-14, is included for comparison. The black line, or design line, is a least square fit of the 5 best performing heaters [10].

When considering the design of a solar air heater, two design parameters are suggested that vary based on collector design [10]. One is the overall heat loss coefficient, U_L, which is related to the heat transfer coefficients in the collector, and which needs to be minimized. This is given by the following equation for a flat plate air heater with air flowing over the absorber [10]

$$U_L = \frac{(U_b+U_t)(h_1h_2+h_1h_r+h_2h_r)+U_bU_t(h_1+h_2)}{h_1h_r+h_2U_t+h_2h_r+h_1h_2}$$

The second parameter is F', which is the useful heat gain coefficient or the ratio of actual energy gain to the energy gain that would result if the absorber plate was at the local fluid temperature. This ratio needs to be maximized to enhance efficiency. The following equation gives F' for the same flat plate air heater.

$$F' = \frac{h_1h_r+h_2U_t+h_2h_r+h_1h_2}{(U_t+h_r+h_1)(U_b+h_2+h_r)-h_r^2}$$

To see how each parameter fits into the overall useful heat gain, the overall collector governing equation, is also given [9].

$$q_u'' = F'(S-U_L(T_f-T_a))$$

where, S is the total energy that is absorbed by the absorber. U_b and U_t are the overall heat transfer coefficients from the top and bottom of the air stream to the outside respectively, h_1 is the heat transfer coefficient from the glazing plate to the air stream, h_2 is the heat transfer coefficient from the absorber to the air stream, and h_r is the linearized radiation heat transfer coefficient from the absorber to the glazing.

5.2. Humidifier designs

Many devices are used for air humidification including spray towers, bubble columns, wetted-wall towers and packed bed towers [10]. The principle of operation for all of these devices is same. When water is brought into contact with air that is not saturated with water vapor, water diffuses into air and raises the humidity of the air. The driving force for this diffusion process is the concentration difference between the water–air interface and the water vapor in air. This concentration difference depends on the vapor pressure at the gas–liquid interface and the partial pressure of water vapor in the air.

Any of the above mentioned devices can be used as a humidifier in the H–DH system. A spray tower for instance consists essentially of a cylindrical vessel in which water is sprayed at the top of the vessel and moves downward by gravity dispersed in droplets within a continuous air stream flowing upward. These towers are simple in design and have minimal pressure drop on the gas side. However, there is a considerable pressure drop on the water side due to the spray nozzles. Also, mist eliminators are always necessary due to the tendency of water entrainment by the air leaving the tower. It is generally known that this device has high capacity but low efficiency. The low efficiency is as a result of the low water holdup due to the loose packing flow [10]. The diameter-to length ratio is a very important parameter in spray tower design. For a large ratio air will be thoroughly mixed with the spray. Small diameter-to-length ratio will let the spray quickly reach the tower walls, forming a film becoming ineffective as a spray. Design of spray towers requires knowledge of heat and mass transfer coefficients as well as the contact surface area of the water droplets. Many empirical correlations and design procedures are given [10].

A spray tower as the humidifier in their H–DH systems was used. The spray tower humidifier by varying the ratio of water-to-dry air mass flow rate and keeping the inlet water temperature and absolute humidity constant was tested. The inlet air temperature (80 °C) was higher than the water spray temperature (60 °C). It was found that increasing the amount of water sprayed increased the absolute outlet humidity. However, further increase in the water quantity resulted in air cooling and this condensed some of the water vapor content in the air. This means a decrease in the absolute humidity, although the outlet air is always saturated.

Therefore, for air heated H–DH cycles there is an optimum value of the mass flow ratio which gives maximum air humidity. This fact promotes the use of multi-stage air heater and humidifier combinations to increase the fresh water production.

Exactly opposite in principle to the spray tower is the bubble column. In the bubble column, a vessel is filled with water and air bubbles are ejected from several orifices located at the bottom of the vessel. Water diffuses into the air bubbles and causes the outlet air to be humidified. These columns are simple in design; however, the diffusion of water into the air bubbles depends on many parameters such as bubble diameter, bubble velocity, gas hold-up (the ratio of air bubbles-to-water volume), water and air temperatures as well as the heat and mass transfer coefficients. In H–DH desalination systems, bubble columns have not been used as humidifiers so far. However, the performance of a single stage bubble column using air bubbles passing through seawater were investigated experimentally [10]. The influence of operating conditions on the vapor content difference and the humidification efficiency was studied, which showed strong dependence on saline water temperature and the air velocity.

Moreover, the inlet air temperature has a small effect on the vapor content difference. The maximum experimentally obtained vapor content difference of the air was 222 g/kg of dry air at 75 °C of water and air temperatures. However, other geometrical factors such as the orifice diameter, number of orifices, water head height and column diameter were not considered. It is important to mention that there are many empirical correlations for these parameters [10]. Therefore an optimum design and performance evaluation study can be carried out before using the bubble columns in H–DH systems.

Wetted-wall towers have been used as humidifier in H–DH systems [10]. In a wetted-wall tower, a thin film of water is formed running downward inside a vertical pipe, with air flowing either co-currently or counter-currently. Water is loaded into the top of the tower and a weir distributes the flow of water aro[illegible] the inner perimeter of the tube that wets the inner surface of [illegible] tube down its length. Such devices have been used for theoretic[illegible] studies of mass transfer, since the contact area can b[illegible]lculated accurately. In Wang et al.'s system [39], heat[illegible] wa[illegible] was distributed onto vertically hanging fleeces made [illegible] polyp[illegible]ylene and trickled downwards. The air move in co[illegible]nte[illegible] the brine through the humidifier and be[illegible]es sat[illegible]ed at the outlet. On the other hand, a different de[illegible] for their w[illegible]d-wall humidifier was used. To improve th[illegible] heat [illegible]d mass exchange process, they covered the woode[illegible] vertical w[illegible]d-walls with a cotton wick to reduce the wa[illegible] flowing veloc[illegible] and use the capillary effect to keep the [illegible]rtical [illegible]lls always wetted. Their design shows higher perform[illegible] [illegible]th abo[illegible]t 100 % humidification efficiency.

To increase the h[illegible]idi[illegible]ation [illegible]cy, packing is typically used. This helps [illegible] increa[illegible]ng the di[illegible]persion of water droplets, the contact area a[illegible] co[illegible] Devices that contain packing material are known a[illegible]cked bed towers and special types that are used to cool water a[illegible]lled cooling towers. These are vertical columns filled with packi[illegible] materials with water sprayed at the top and air flows in counter or cross flow arrangement. Packed bed towers have been used by many researchers as a humidifier device in H–DH desalination systems because of the higher effectiveness. Different packing materials have been used as well (Ceramic raschig rings, Wooden shaving, Wooden surface, Wooden slates packing, Honeycomb paper, Indigenous structure, Thorn trees, Corrugated cellulose material, Canvas, HD Q-PAC, Plastic packing, and Corrugated cellulose material) [10]. The factors influencing the choice of a packing are its heat and mass transfer performance, the quality of water, pressure drop, cost and durability. Over the last 30 years, there has been a gradual change in the types of fill used in packed bed towers [10]. The most dramatic change has been the introduction of film fills that provide significantly higher thermal performance through the increase of water-to-air contact area and a reduction in pressure drop. However, in H–DH desalination application, due to high fouling potential, these benefits are forfeited and the older splash-type fill packing is used. A history of the development of packing materials was presented and the performance of various film-type fills was investigated [10]. The Merkel, Poppe and epsilon- NTU heat and mass transfer methods of analysis are the cornerstone of cooling tower performance evaluation.

To evaluate the performance of an air humidifier, an efficiency or effectiveness should be used. Many researchers defined humidifier efficiency as [10],

$$\eta = (\omega_{out} - \omega_{in})/(\omega_{out,sat} - \omega_{in})$$

where, ω_{out} is outlet absolute humidity; ω_{in} is outlet absolute humidity; $\omega_{out,sat}$ is outlet absolute humidity at saturation.

The maximum humidity differen[illegible] in this definition assumes that the outlet air is saturated [illegible] air temperature. This definition is basically used f[illegible] evaporati[illegible] coolers [10] where unsaturated air passes through [illegible] packing [illegible]terial wetted with water that is sprayed at [illegible] top of [illegible] pack[illegible]g. The sprayed water is circulated and at st[illegible]y stat[illegible] condi[illegible]s temperature reaches the wet-bulb temp[illegible]ture [illegible] the inlet air. In this case the air temperature de[illegible]ase[illegible] it app[illegible]ches the wet-bulb temperature. This hu[illegible]ifier effi[illegible]cy [illegible]nnot be used if the inlet air is saturated [illegible] there wi[illegible] no humidity increase. However, if the inlet water te[illegible]erature is higher than the air temperature or steam [illegible]jected in[illegible]r stream, the air in this case will be heated an[illegible]umidified. In [illegible]s case also, the air will be near the s[illegible]ration condition, thus the efficiency definition described a[illegible]e will n[illegible] represent how efficient is the humidification pro[illegible]

[illegible] Dehumidifiers

The types of heat exchangers used as dehumidifiers for HDH applications vary. For example, flat-plate heat exchangers were used by Müller-Holst et al. [17]. Others used finned tube heat exchangers [10]. A long tube with longitudinal fins was used in one study [10], while a stack of plates with copper tubes mounted on them in another study [10] used a horizontal falling film-type condenser. Direct contact heat exchangers were also used as a condenser in some other studies [10] in combination with a shell and tube heat exchanger to provide enhanced condensation and improved heat recovery for the cycle.

A flat plate heat exchanger made of double webbed slabs of propylene was used by Muller-Holst et al. [17] in his HDH system. The distillate runs down the plates trickling into the collecting basin. Heat recovery is achieved by transferring heat to the cold sea water flowing inside the flat plate heat exchanger. The temperature of sea water in the condenser increases from 40 to 75 °C. In a similar study, Chafik [18] used seawater as a coolant where the water is heated by the humid air before it is pumped to the humidifiers. Three heat exchangers were used in three different condensation stages.

An additional heat exchanger is added at the intake of sea water (low temperature level) for further dehumidification of air. The heat exchangers (or dehumidifiers) are finned tube type air coolers. They developed a theoretical model by using TRNSYS to calculate heat transfer coefficients from both the hot- and cold-sides of the heat exchanger, from which the system operating conditions were set. It is important to note that to withstand corrosive nature of seawater; stainless steel is used for frames, collecting plates, while the fins are made of aluminum. In addition, special attention was exercised to avoid leakage of distillate water.

Different designs of condensers in a H–DH cycle were used by Farid et al. [19]. In a pilot plant built in Malaysia, the dehumidifier

was made of a long copper galvanized steel tube (3 m length, 170 mm diameter) with 10 longitudinal fins of 50 mm height on the outer tube surface and 9 fins on the inner side. In another location, they used a simplified stack of flat condenser made of 2×1 m^2 galvanized steel plates with long copper tubes mounted on each side of the plate to provide a large surface area. The condenser size was made large, particularly to overcome the small heat transfer coefficients both on the air- and water-sides due to relatively low air velocity, as well as low water flow rates.

In another design, the dehumidifier was made of 27 m long copper pipe having a 10 mm OD, mechanically bent to form a 4 m long helical coil fixed in the PVC pipe. The preheated feed water was further heated in a flat plate collector. The hot water leaving the collector was uniformly distributed over a wooden shaving packing in a 2 m long humidifier. It is important to note that the condenser or dehumidifier was made of hard PVC pipes connected to form a loop with the blower fixed at the bottom. The condenser was made of a copper pipe mechanically bent to form a helical coil fixed in the PVC pipe.

Two types of condensers were reported in another study [10]. These were constructed from galvanized steel plates for both the bench and pilot units. In the pilot unit, a copper tube having 11 mm OD and 18 m long was welded to the galvanized plate in a helical shape. The tube outside diameter and length in the bench unit were 8 mm and 3 m, respectively. Either one or two condensers, connected in series, were fixed vertically in one of the ducts for both the units. In one unit, the condenser was simply a 3 m long cylinder having a diameter of 170 mm and made of galvanized steel plates. Ten longitudinal fins were soldered to the outer surface of the cylinder and nine similar were soldered to the inner surface. The height of inside and outside fins was 50 mm. The thickness of the plate that was used to make the cylinder and the fins was 1.0 mm. A copper tube having 9.5 mm inside diameter was soldered to the surface of the cylinder. The condenser was fixed vertically in the 316 mm diameter PVC pipe which is connected to the humidifier section by two short horizontal pipes.

Bourouni et al. [20] used a condenser made of polypropylene which was designed to work at low temperatures (70–90 °C) for a HDH system. It is similar to a horizontal falling film-type condenser. At the top of the dehumidifier, the hot humid air is forced down where the distilled water is recovered. It is important to note that heat recovery in an HDH system requires a larger heat transfer area for improving the overall system performance. For this reason, 2000 m of tubes are used in the evaporator, while 3000 m of tubes in the condenser.

The system of two solar heaters, one for heating water and the other for heating air [illegible]. The condenser, that uses seawater for cooling, consists of a chamber with a rectangular cross section. It contains [illegible] rows of long cylinders made of copper in which the feed water flows. Longitudinal fins were soldered to the outer surface of the cylinders. The condenser is characterized by heat-transfer surface area of 1.5 m^2 having 28 m as a total length of the coil.

Packed bed direct contact heat exchangers were used in a few researchers [10], because the film condensation heat transfer is tremendously degraded in the presence of non-condensable gas. An additional shell and tube heat exchanger is used to cool the desalinated water from which a portion is re-circulated and sprayed in the condenser.

The governing equations for the dehumidifier in differential form were explained. Also, design correlations for both friction factor and heat transfer coefficients that can be used for dehumidifiers were summarized [10].

The standard method that considers finned-tube multi row multi-column compact heat exchangers was developed. it predicted heat and mass transfer rates using Colburn *j*-factors along with flow rate, dry and wet bulb temperatures, fin spacing and other dimensions. The air side heat transfer coefficient is based on log-mean temperature difference for the dry surface whereas under the condensing conditions, the moist air enthalpy difference is used as a driving potential.

Neural network techniques and the experimental data were used and collated, to create a trained network that predicted the exchanger's heat rate directly [10]. Remarkably accurate results were obtained as compared with the method of using correlations of heat and mass transfer coefficient and Colburn j factors. They focused on the exchanger heat rate since it is the value ultimately desired by users. A significant improvement in the accuracy of predictions compared to the conventional j factor approach was demonstrated, e.g., 56.9% less error for drop wise condensation and 58.6 % less error for film wise condensation have been reported.

6. Alternate cycles resembling the H–DH process

6.1. Dew-evaporation technique

Beckman has [illegible] and investigated a desalination technology that works on the humidification dehumidification principle [illegible]. They call it the 'Dew-Evaporation' technique (Fig. 26). Unlike the H–DH process, it uses a common heat transfer wall between the humidifier (which they call the evaporation chamber) and the dehumidifier (which they call the dew formation chamber). Latent heat of condensation is directly recovered through this wall for the humidification process. It is reported that the use of this common heat transfer wall makes the process energy efficient.

In this process the saline water, after being preheated using the exit distillate water stream, wets the heat transfer wall and is heated by means of the latent heat of condensation from the dew-formation chamber. It then evaporates into the air stream, humidifying it. The humidified air stream is then heated using an external source and is fed to the dehumidifier at a temperature higher than the temperature of air leaving the humidifier. While, heat is directly recovered from the dew-formation tower, it should be noted that the condensation process itself is relatively ineffective. The dehumidified air exits the tower at a high temperature of around 50 °C (compared to 30–35 °C in a H–DH cycle). Also, the coupling of the humidification and dehumidification processes sacrifices the modularity of the H–DH system and

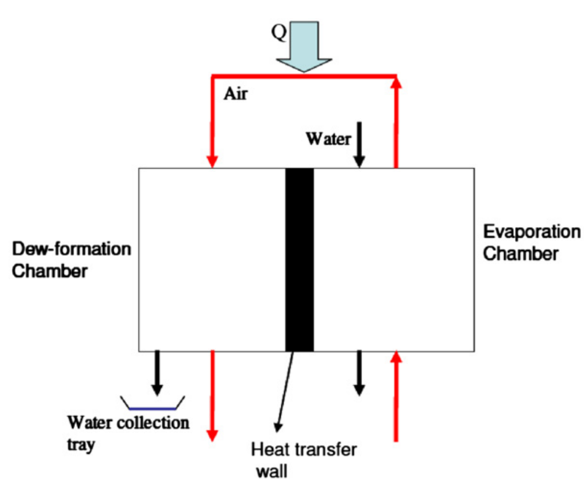


Fig. 26. Dew-evaporation process [10].

the related opportunities to optimize subsystem design and performance separately. However, despite these possible drawbacks this technology appears to have some potential.

6.2. Diffusion-driven desalination technique

Investigators at University of Florida have patented [10] an alternate desalination process that works on the H–DH principle. They call it the 'diffusion driven desalination' (DDD) process. The system is similar to the closed-air open-water HDH cycle, but it uses a direct contact dehumidifier in place of the non-contact heat exchanger normally used for condensation in the H–DH systems. The dehumidification process uses a portion of the distilled water produced from the cycle as a coolant. A chiller is used to provide the distilled water at a low temperature. In a similar system, an H–DH system with a direct contact dehumidifier having ceramic Raschig rings as the packing material had earlier proposed [10]. The specific energy demand of the DDD process (GOR ~ 1.2) is higher for this cycle than for a normal HDH cycle in which the latent heat in the dehumidifier is not recovered.

6.3. Atmospheric water vapor processors

As explained above, various processes that extract the humidity from ambient air were reviewed [4]. These processes are called dew collection processes and the system is sometimes called an atmospheric water vapor processor (AWVP). Three different methods have been applied in these systems

(1) surface cooling using heat pumps or radiative cooling devi[illegible]
(2) using of solid/liquid desiccants to concentrate the moisture [illegible] atmospheric air before condensing it out; and
(3) convention-induced dehumidification.

While it may seem promising to take advan[illegible]e of [illegible] that is already humidified and a cycle which consi[illegible] of [illegible]ehumid[illegible]fication (which is by itself exothermic), [illegible]he majo[illegible]awbacks accompany this concept of water extra[illegible] The absolu[illegible]umidity in ambient air found in most plac[illegible] aro[illegible] the world is low, and hence to produce a reaso[illegible]e amount [illegible] water a large amount of air needs to circula[illegible] through the proc[illegible]ss equipment. Also, even though the dehu[illegible]ficati[illegible] process is exothermic the possibility of extracting any [illegible]odynam[illegible] advantage from it exists only when a lo[illegible]mpe[illegible]e si[illegible] is available.

7. Possible impro[illegible] HDH cycle

We observe that mos[illegible]udies in the literature consider cycles that heat the air before th[illegible] humidifier (in single or multistage), which causes the heat recovery to be reduced since the air gets cooled in the humidifier. If the heater is placed after the humidifier (Fig. 27), saturated air from the humidifier is heated and sent to the dehumidifier. Seawater gets heavily preheated in the dehumidifier and the air in turn is heated and humidified in the humidifier [10].

There are two advantages to this cycle: (1) the condensation process occurs in a higher temperature range than the evaporation process, and hence heat is recovered efficiently; and (2) the enthalpy curves for humid air are such that a large temperature rise can be achieved easily for this cycle. This can be observed from the enthalpy-temperature diagram shown in Fig. 28. Even for water heated cycles, the humidification process occurs at higher air temperatures than the dehumidification process and the heat recovery is affected by that as well. Thus, the proposed cycle should have better heat recovery than all the systems presented in the literature. It can be observed that all the HDH systems in literature operate at atmospheric pressures only.

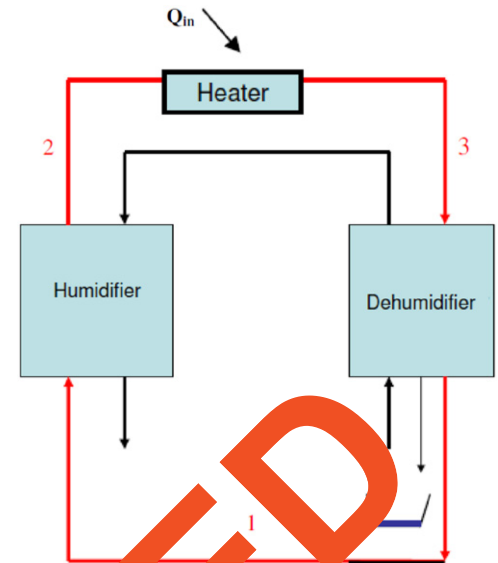


Fig. 27. [illegible] heate[illegible]OW HDH process [10].

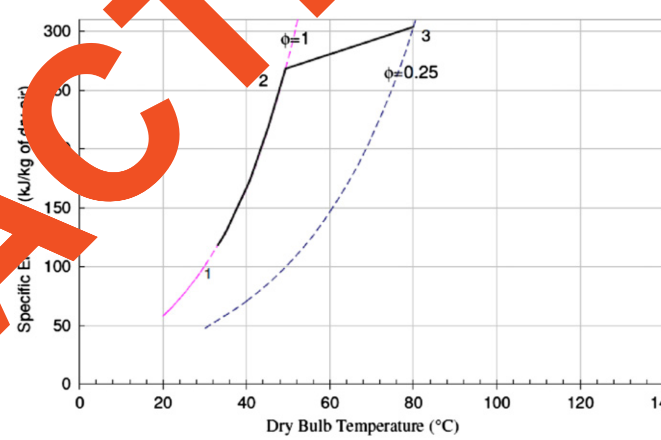


Fig. 28. Psychometric representation of the proposed process in an enthalpy versus dry bulb temperature chart [10].

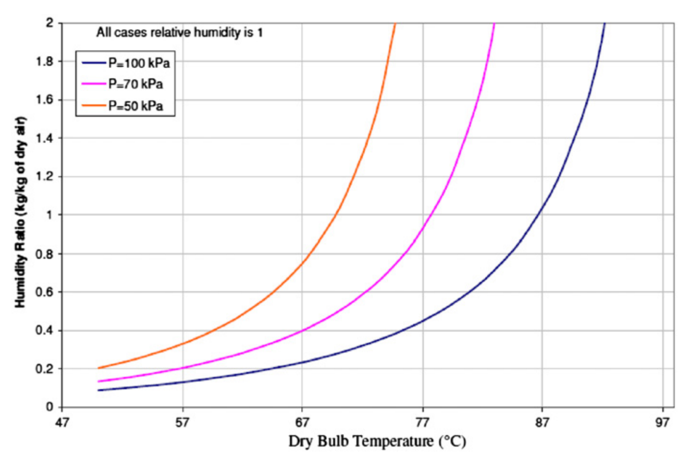


Fig.29. Effect of pressure on water carrying capability of air [10].

Table 11
Variables affecting performance of desiccant dehumidifiers and AWVP analogs to these variables [6].

Desiccant dehumidifier variables	AWVP desiccant variables
1. Process air moisture. 2. Process air temperature. • Lower inlet temperatures enhance water extraction. • Higher inlet temperatures reduce performance.	1. Ambient (outdoor) air moisture. 2. Outdoor air temperature. • Inlet temperature may have diurnal and seasonal variation which must be accounted for in the system design and water output specifications.
3. Process air velocity through desiccant (2–3 m/s). • More water is extracted at low velocities but this efficiency must be traded off against need for larger equipment for slower air flow. • If process air has a high moisture content the performance gain for slower air flow with larger equipment may not be cost effective. • Higher velocities result in higher moisture removal rate.	3. Natural wind velocity through desiccant or fan assisted to 2–3 m/s. • Focus is on maximizing moisture removal rate, therefore bias is fortuitously towards smaller and less equipment expensive.
4. Reactivation air temperature. • Heating desiccant causes it to release moisture. • Heater capacity may need to be increased in cooler weather to maintain performance level.	4. Outdoor air temperature will often be lower th mercial/industrial applications so that a larger desiccant unit w be requ for AWVP unless additional energy is input for regeneration e desiccant. efficiency, the desiccant should be as dry as possible when r osed to th rocess air stream.
5. Reactivation air moisture. • Usually design for minimum moisture content of inlet reactivation air and to prevent leakage of moisture from reactivation to process side.	5. Outdoor air moisture co t at a VP site ld usually be relatively high so moisture of air enterin ctivation w b gher than optimum for standard dehumidification ap —therefore tively high reactivation temperature may be required.
6. Reactivation air velocity through desiccant (1–3 m/s) • reactivation air is simply expelled to the atmosphere with no attempt made to condense the water molecules that were collected.	6. Air ve ty through iccant: • set a ream at m um required to transport heat to desiccant, to optimize energy sumpti f subsequent condensation process.
7. Surface area or volume of desiccant exposed to reactivation and process airstreams. • Moisture removal rate is a function of amount of desiccant. • Air friction increases with surface area exposed to air stream. • Both granular and liquid desiccants promote turbulent flow wh set the condition that air flow resistance increases as square o veloci • Some designs promote laminar flow but even so resistance port to desiccant bed depth. • General principle is to ensure that energy consum vs air m re removal capacity is optimized.	7. s for dehumidifier
8. Desiccant sorption/desorption characteris s. • Designers may combine two or more d cants in same u increase range of temperature and humidity itions r use of the quipment. • Solid adsorbent performance deg over as surfaces and crevices fill with atmospheric dust that byp tion. Organic vapors can alter d rfaces. • Liquid absorbents ma nge c ically ov e years with exposure to chemical pollutants e air ing processed to capture water molecules.	8. Customize desiccant combinations to climatic conditions (air temperature and absolute humidity) at the site. Plan for periodic replacement of desiccants.

Table 12
Some Engineering information for AWVP methods [6].

Engineering information	Type 1-cooled surface	Type 2-desiccants	Type 3-convection
– Range of efficiencies – Coefficient of performance (Cop), – C_P=energy sought/ energy cost – efficiency, η,	– Cop=2.0–4.5 Harriman dehumidifiers – Cop=3.2 ADS The Rainmaker – C_P=324–420 Seawater Greenhouse) – η=0.19–0.20 DRY-200 dehumidifiers) – η=0.20–0.40 dehumidifier used inAWVP trials was more efficient at higher air temperatures	– CP is not widely used to rate desiccant-type humidifier performance – η=0.35 (liquid desiccant dehumidifier) – η=0.68(solid desiccant dehumidifier)	– C_P is not used at present. η=0.39
Energy requirements (kWh/m^3 water)	– 270–500 (refrigerant technology) – 2.6:15 (deep ocean water coolant – 0 for surface cooled by radiation	– 280 liquid desiccant) – 1305 (DST R-122, solid desiccant)	1800

The humidity ratios are much higher at pressures lower than atmospheric pressure. This is expected to increase the water production many times for the H–DH cycle [9]. For example, at a dry bulb temperature of 60 °C, the humidity ratio at 50 kPa is ~150% higher than at atmospheric pressure, as in Fig. 29 [10].

In conclusion, Solar humidification dehumidification desalination technology has been reviewed in detail in this paper. From the present review it is found that among all H–DH systems, the multi effect CAOW water heating system is the most energy efficient. For this system, the cost of water production is ~US $ 3–7/m^3 [10]. Even though this is higher than that for RO systems working at similarly small capacities (5–100 m^3/day), the H–DH system has other advantages for small-scale decentralized water production. These advantages include much simpler brine pretreatment and disposal requirements and simplified operation and maintenance. Methods to further improve the performance of the H–DH cycle have also been proposed in this paper. These methods include sub-atmospheric and multi-pressure operations. Further research needs to be carried out to realize the full potential of these ideas and the H–DH concept in general.

8. Applications to regions of water scarcity

The natural range of absolute humidity is from 4 to 22 g of water per cubic meter of moist air with many population centers having values between 5 and 10 g per cubic meter. Absolute humidity (meteorological normal) in regions of low precipitation (annual average 300 mm or less) ranges from 4.0 g water vapor per cubic meter of surface air in the atmosphere to 21.2 g/m^3 [6]. Potential water production rate (in l/d) is

$$\text{Daily water volume/day} = \text{Airflow }(\text{m}^3\,\text{s}^{-1} \times 86{,}400\,\text{s day}^{-1}) \times \text{Absolute humidity }(\text{g m}^{-3}) \times 1/1000\,\text{l g}^{-1}$$

where, the definition of • efficiency,

$$\eta = \frac{\text{Amount of water extracted per unit time}}{\text{Total moisture content of air processed per unit time}}$$

The above establishes suitability of an air water vapor processing machine for a given purpose in a specific location. Consider two different scenarios involving locations in Chile and Kenya. Information from 1994, reveals that [illegible]4% of the urban population in Chile has access to safe drinking water but only 37% of the rural population enjoys this access. In Kenya, 67% of the urban and 49% of the rural population has safe drinking water.

A 40% efficient machine in the surroundings of Antofagasta (absolute humidity [illegible].9 g m^{-3}) with air flow of 10 m^3/s would produce 37[illegible] water per day. At a modest consumption of 50 l per person per day, 75 people could have their domestic water requirements satisfied. A family of six living in a considerably more humid part of the world, but short of safe drinking water, such as Garissa, Kenya (normal absolute humidity 17.0 g m^{-3}, consuming 900 l per day for drinking, kitchen, laundry, and bath would need a 60% efficient AWVP machine capable of 1 m^3/s air flow (Table 11).

Table 12 summarizes engineering information for AWVP (The wide range of efficiencies, and energy requirements.).

Most designs are adaptable to various scales of water supply from one person to communities of hundreds or thousands. Sizes of AWVP plants will follow from water supply planner's decisions on how much distribution infrastructure is desirable.

Each building could have its own small AWVP plant, avoiding entirely the need for municipal potable water mains. Or, a neighborhood could have a large, central AWVP plant from which a distribution infrastructure is built and maintained. Air handling requirements for one person's daily water needs could be accommodated in a small, portable unit while an AWVP plant capable of supplying hundreds of people might be the size of a large industrial building or multi-story office tower.

Dehumidification engineers optimize designs by hybridizing surface cooling and desiccant technologies [10]. The two methods complement each other. AWVP needs the two working together because rather than simply exhausting moisture rich air, the device must condense water out of the so-called scavenging (exiting) air stream. Blending economies are likely to be inherent in AWVP designs.

Table 13
Decision table for initial consideration of blending cooling and desiccant technology in an AWVP device according to electricity costs for powering surface cooling compressors/fans and thermal energy costs for reactivating desiccants [6].

Energy source/cost	Cheap	Costly
Electric power	Cooling	Desiccant
Thermal energy	Desiccant	Cooling

Table 14
Decision table for initial consideration of the most economical AWVP method, given certain ambient conditions of air temperature, ta, and relative humidity, ϕ. Low ϕ is taken as being less than 50% and low t_a means close to the freezing point of water [6].

Ambient air	Low ϕ	High ϕ
Low t_a	Desiccant	Desiccant
High t_a	Cooling or desiccant	Cooling

Some references in Table 3 quantified product water output. Cooled surface designs claimed outputs up to 5,860,000 l/d. The solid desiccant system would provide up to 100 million l/d. The inventors suggested aquifer recharge as an application. The liquid desiccant processor claimed a daily potential output of 1.7 million liters. Convection-based AWVP devices could provide up to 31 million liters daily. These amounts rival the 284,000–45 million liters daily capacity of reverse osmosis desalination plants.

Choice of methods is an engineering decision dependent on local climatic conditions and economic factors such as capital, operating, and energy costs. A first consideration of energy costs while blending methods is in Table 13. Air temperature and relative humidity aspects of combining processes are in Table 14. In a hybrid system, the surface cooling subsystem must be capable of coping with the sensible heat load of the desiccant subsystem.

9. AWVP water costs

Potable water costs ranged from $0.09/m^3 in Jakarta to retail supermarket bulk drinking water in Canada at $100/m^3 [6]. AWVP water produced with deep seawater coolant is relatively expensive at about $5.32–$12.24/m^3. Profit generating ancillary activities such as agriculture, horticulture, aqua-culture, marine-culture, or water sales were ignored. Costs associated with The Rainmaker2 were estimated. Advanced Dryer Systems, Inc. (ADS) priced their heat pump based device at US$1500 and estimated energy costs at $0.07/kWh [10]. Using a $500 capital, a 15 year lifetime, and energy consumption (ADS) of 480 kWh/m^3 fresh water cost of water would be $47/m^3. Although residential dehumidifiers with similar fresh water outputs as The Rainmaker2 can be purchased for $250, they are not intended for potable water production. Johnson pointed out that these do not

Table 15
A comparative summary of Studies conducted on extracting water from moist air [3–43].

Reference	Bed-desiccant type	Productivity, l/d	Place
Hamed et al. [7]	– Sandy bed impregnated with calcium chloride	– Liter per m^2 of pure water	Taif, KSA
Kabeel [13]	– Sandy bed impregnated with 30% concentration calcium chlo-ride – Surface area of 0.5 m^2	1.2 l fresh water per square meter of glass cover per day in the climatic conditions of Tanta city, Egypt which is mostly humid	Tanta city, Egypt
Kabeel [28]	– Glass pyramid shape with a multi-shelf solar system – Two pyramids were used with different types of beds on the shelves. The beds are saturated with 30% concentrated calcium chloride solution – The pyramid sides were opened at night to allow the bed saturated with moist air and closed during the day to extract the moisture from the bed by solar radiation – The bed in the first pyramid was made of saw wood while it is made of cloth in the second pyramid with the same dimensions	– Results have shown that the cloths bed absorbs more solution (9 kg) as compared to the saw wood bed (8 kg) – The system produces about 2.5 l/(day m^2)	Tanta city, Egypt
Aristov et al. [31]	– Selective composite adsorbent was used – Ultra-large pore crystalline material MCM-41 as host matrices and calcium chloride as a hygroscopic salt	– The results of their lab-scale t[illegible] have demons[illegible] feasibility of fresh water pr[illegible]ction w[illegible] an outpu[illegible] 3–5 t of water per 10 t of the dry so[illegible]ay – Adsorption capacity [illegible]e new [illegible]posites [illegible] high as 1.75 kg/kg dry ads[illegible]nt, which i[illegible]an composites synthesized by [illegible] and calciu[illegible]ride and the adsorption rat[illegible] the [illegible] composites is also found attractive – Productivity more than 1[illegible]/m^2 of the solar collector area	Not mentioned
Hamed [29]	– Forced convection adsorption, using packed porous bed	– The [illegible]duction of water from air on a continuous, 24-hour basi[illegible]sing more c[illegible]act adsorption units by applying forced conv[illegible]ion adsorpt[illegible] in packed porous bed is proposed	Mansoura, Egypt
Abualhamayel and Gandhidasan, [11]	– Blackened, tilted surface and is covered by a single glazin[illegible] with an air gap of about 45 cm – $CaCl_2$ was used as absorbant	– 1.92 kg/[illegible]ter productivity	Dhahran, KSA
Sultan [8]	– Non conventional method for 24 h productio[illegible] – Bed consists of vertical multi-layer cloth m[illegible]ials impregnated with $CaCl_2$ solution of diff[illegible] concentrations	[illegible]he system eff. Increases with the concentration of solution, [illegible]nd decreases with the increase of regeneration air velocity [illegible]nd the absorption temperature.	Mansoura, Egypt
Gad et al. [12]	– Thick corrugated layer of cloth[illegible] – CaCl2 concentration 30–40%[illegible]	– 1.5 L/m^2 day-water productivity – Overall eff. 13–17%	Mansoura, Egypt
Elsarrag and Al Horr [40]	First by collecting conden[illegible] water, secon[illegible]ovel tilted solar absorption/desorp[illegible] system, Calcium c[illegible]ide is used as the desiccant and [illegible]rrugat[illegible]lackened surface is used to heat the desiccant i[illegible]tim[illegible]	– 7.2 l/day per kW cooling.(for the first method). – 0.18 l/min per m^2 of solar collector area(second method)	Doha, Qatar
Gordeeva et al. [41]	– New selective wate[illegible]ents for [illegible]nwater production from the[illegible]phere – Absor[illegible]: an[illegible]drous S[illegible] – Dr[illegible]eight of[illegible]e sorbents [illegible]as equal to 250–350 g. – Ca[illegible] (23.7[illegible] [illegible]2 (25.9%), [illegible]1203 [illegible]2 (24.5%), C LiB[illegible]8%), SiO2	– Feasibility of this method with the output of 3–5 kg of water per l0 kg of the dry sorbent per day – The results presented demonstrate the feasibility of efficient closed cycle of freshwater production with an output of 3–5 kg per 10 kg of sorbent	Nevosibirsk, Russia
Zheng et al. [43]	– Silica gel (777.3916 m^2/g) – Composite(silica gel+CaCl2 with ration of 7:3 respectively)=(768.9117 m^2/g) – About 9 kg of silica gel and its composite were respectively loaded into two adsorption towers in the same size and capacity	– 8 tons of fresh H2O needs about 500 KW, which is smaller than waste heat from ship's engine – Av. day output of product water from 9 kg silica gel is 0.5 kg – But using composite compounded by silica gel with CaCl2, can greatly be enhanced by about 3:4 times of that on silica gel	Marine, RH is always >70%
Kobayashi [35]	– Extraction of water from Air (EWA) using adsorbent, technology – EWA is made of modular cassettes with different sizes	– EWA is made of modular cassettes with capacity up to 1000 m^3/day – EWA could be operated at ambient range between 5 and 45 and at RH of 20% and more, while at RH=60% the system gives its max. capacity – EWA can provide a reasonable solution for water supply in arid regions	– General design – Patent technology

filter adequately the airflow or provide carbon filtration and water mineralization (Table 15).

10. AWVP water quality

Water extracted from the atmosphere may not be safe to drink. Processing large volumes of air can concentrate pathogens and debris. Stored water may suffer contamination. Standard water treatments such as chlorination or disinfection by ultra-violet light or ozone may be required. The condensate can be mineralized to avoid the flat taste of distilled water and for gastric health. National water quality standards must be met. Potable water testing for The Rainmaker2 found nitrite nitrogen was 0.094 mg/l, nitrate nitrogen was 0.046 mg/l, lead was <0.00100 mg/l, and copper, total coli-forms, and E. coli were undetected, all within United States Environmental Protection Agency standards.

11. Energy source for H–DH process

11.1. Principle of the process

The most promising recent development in solar desalination is the use of the humidification (H)–dehumidification (DH) process. The principle of functioning of the HD process has been reviewed by Bourouni et al. [20]. The HD process is based on the fact that air can be mixed with large quantities of water vapor. The vapor carrying capability of air increases with temperature:1 kg of dry air can carry 0.5 kg of vapor and about 670 kcal when its temperature increases from 30 °C to 80 °C. When flowing air is in contact with salt water, a certain quantity of vapor is extracted by air, which provokes cooling. Distilled water, on the other hand, may be recovered by bringing the humid air in contact with a cooled surface, which causes the condensation of part of the vapor in the air. Generally, the condensation occurs in another exchanger in which salt water is preheated by the latent heat of condensation. An external heat contribution is therefore necessary to compensate for the sensible heat loss.

The H–DH technique is especially suited for seawater desalination when the demand for water is decentralized. Several advantages of this technique can be presented which include flexibility in capacity, moderate installation and operating costs, simplicity, and possibility of using low grade thermal energy (solar, geothermal, recovered energy or cogeneration). In this process, air is heated and humidified by the hot water received from a solar collector. It is then dehumidified in a large surface condenser using relatively cold saline feed. Most of the latent heat of condensation is used for preheating the feed.

11.2. Non-solar methods of extracting water from humid air under atmospheric condition

Prior to focusing on the details of the different types of solar HD processes and their analysis, we briefly review work aimed at using the humidity in the atmosphere as a source of fresh water and methods for extracting the water from humid air. Methods for water extraction from humid air include mechanical, refrigeration (absorption and vapor compression), adsorption and absorption

11.2.1. Atmospheric water vapor processing (AWVP)

As explained above, three classes of "processor machines" for potable water production were identified. The machine design types mentioned are based on

- surface cooling by heat pumps or radiative cooling;
- concentrating water vapor through use of solid or liquid desiccants, and
- inducing and controlling convection in a tower structure. No costs or capacities for these machines are mentioned, but energy requirements stated for the three classes of machines mentioned are relatively higher than those of solar-based H–DH process [6].

11.2.2. Dew collection

A scheme for large-scale dew collection as a source of fresh water supply was reported [4]. In the desert environment, dew collection takes place due to night sky radiation cooling. This, however, results in an insufficient quantity of water production. A more efficient method proposed would be to pass deep-sea cold water through suitable heat exchangers for dew condensation. A heat exchanger field of [illegible] m^2 can condense 643 m^3 of dew over a period of 24 h. Cold water for dew condensation may be obtained from a depth of [illegible] m. Three 200 kW wind machines power the pumping of [illegible] kg/h of this cold water [3].

11.2.3. Adsorption method

A study to extract water from wet air based on the adsorption principle was reported [4]. A two-phase cycle comprised of a nocturnal phase and a diurnal phase was proposed. In the nocturnal phase, an adsorbent composite material, type "A", is exposed to the surrounding atmosphere in which the temperature and relative humidity rate can vary. Material "A" is humidified by physicochemical adsorption. In the diurnal phase, solar radiation heats up the wet composite material "A" to about [illegible]. The water contained in the material is drawn up and it condenses on a cold plate. Experimental investigations with a certain type of composite material ("A") under the conditions of 20 °C temperature and relative humidity of 50% yielded 1 l/m^2/d of drinking water. The quantity of water increased to 2–4 l per m^2 of material surface if the relative humidity is increased to 80% and if another composite material (type "B") is used.

11.2.4. Absorption–refrigeration method

Among the absorption–refrigeration methods to extract fresh water from humid air, a non-conventional method suitable for collecting the humidity from air in hot regions was presented [4]. In this process, water is a by-product of a cycle, originally used in air-conditioning. A solar driven LiBr-H2O absorption-cooling machine is used with an open absorber where the ventilation air is dehumidified by direct contact with a concentrated LiBr-H2O solution. The diluted solution is regenerated in a generator (concentrator) where the collected water is recovered to allow the concentrated solution to be recycled. The recovered vapor is condensed (fresh water by-product) and the condensation heat is re-used to promote the required cooling effect for the air-conditioning evaporator. Besides its efficient air-conditioning function, the process contributes to decentralized fresh water production in hot regions. The byproduct water production amounts to 3.1 l/m^2/d of collector area, which is higher than that of basin solar stills.

11.2.5. Vapor compression–refrigeration method

A novel desalination concept combining the principles of HD and mechanical vapor compression refrigeration was proposed [4]. They constructed a laboratory prototype unit to analyze and study the concept. Their process combines the principles of intensive evaporation and vapor compression refrigeration with a heat pump (mechanically intensified evaporation MIE).

This process re-uses latent heat of condensation of water in successive evaporation chambers, and experiments have indicated that the prototype was successful.

A study to investigate the combination of desalination with cooling and dehumidification air-conditioning was conducted by Khalil [22] for the climatic conditions of the United Arab Emirates coastal regions. The quantity of fresh water obtained depends on different parameters such as properties of the humid air, air velocity, cooling coils, surface area, and heat exchange arrangement. To achieve the maximum condensate yield, the heat and mass transfer mechanisms were analyzed and coil conditions optimized.

11.2.6. Absorption method

Among the absorption-based techniques, Abualhamayel and Gandhidasan [11] proposed the use of a suitable liquid desiccant to extract fresh water from humid air. The night-time moisture absorption and the daytime moisture desorption take place in the same unit. The performance of the unit was predicted analytically for typical summer climatic data in Dhahran, Saudi Arabia, by solving the energy balance equations. For given operating conditions it was shown that it is possible to obtain about 1.92 kg/m^2 of the unit. The influence of absorbent concentration and flow rate on the performance of the system was analyzed, and it was found that the increase in the absorbent solution flow rate increases the rate of absorption of water from the atmosphere but decreases the desorption rate of water during daytime operation. Further study is required to determine the economic feasibility of the system.

11.2.7. H–DH using hydrophobic capillary contactors

Novel methods of desalination based on the H–DH principle have been proposed and studied by other investigators. A new desalination process consisting of air H–DH using hydrophilic or microporous hydrophobic hollow fibers was studied [4]. Hot saline water is passed through hollow fibers in a [illegible] air-sweep pre-vaporation process, the saline water being heated by waste heat, solar energy or any other sources of energy.

The flux of water through the hollow fibers was in the range of 1.5–3.0 l/m^2 h, with water temperature being [illegible]5–65 °C. The calculated energy requirement for pumping air and water in a pilot plant unit of capacity 6.3 [illegible] with [illegible] m^2 of anion exchange hollow fibers was about 2 kWh/[illegible] when hot water temperature was 60 °C [4]. Experiments indicated high mass transfer efficiency for both humidification and dehumidification.

11.3. Solar H–DH

A solar still developed in the first stage in the Central Salt and Marine Chemicals Research Institute, Gujarat, India, had a productivity of 2.94–3.91 l/m^2 of still area, depending upon the variations in the intensity of solar radiation. Certain drawbacks of the solar still technique were overcome in the solar-powered HD technique. In the first stage of development of the HD technique, a 3 L/d (24 h) capacity experimental unit was manufactured having a packed tower with a packing height of 30 cm, using Raschig rings as packing material. The total height of the humidifier was 60 cm, with 15 cm top and 15 cm bottom heads. The humidification unit was coupled with a surface condenser (dehumidifier). The distillate collected from the unit had a concentration of less than 50 ppm of salt. An electric heater was used to heat the brine. From experimental runs, it was determined that for lower temperatures of around 55 °C, a liquid–gas ratio (L/G) of the order of 3 was suitable. This unit had a production of 3.4 L/d for a brine temperature of 60 °C. A second unit was constructed with a capacity of 136 L/d (24 h). Measurements showed that the rate of production of fresh water increased with the increase in temperature of brine, if other conditions such as liquid and gas rates were kept constant. The Reynolds number for air flow calculated for the 3.4 l capacity unit was 285 and for the 136 l capacity were 300. From the experiments on the 136 l/d capacity unit, the rate of production of fresh water obtained was about 61.2 l/d for a brine temperature of 59 °C and a L/G ratio of 2.0. The production was lower than the designed capacity as the heat transfer area provided in the condenser unit was not sufficient, even though the heat transfer coefficient was relatively high, so that complete condensation of water vapor was not achieved. Results showed that an L/G of 3 was favorable, resulting in production of 72 l/d. A pilot plant with a capacity of 4540 l/d of fresh water was designed for further [illegible].

Due to the scarcity of water and fossil fuel in the Canary Islands, solar-assisted desalination was studied on the Islands. A forced convection HD process was analyzed [illegible]. The process of forced convection solar distillation differs from the conventional still in that vapor from hot water is absorbed by flowing air and dragged out to an external cooler where it is collected as condensate. The authors studied the effect of convection during water evaporation and vapor condensation at an external condenser (Figs. 30 and 31). The authors developed two simulation models for the proposed process and predicted its output in terms of temperature and humidity. A simplified model using mass and energy balance relationships is presented as well as a general model that predicts the system behavior. A method for determining energy and exergy efficiency has been included, which is also applicable to other solar collection and conversion processes. Still dimensions were 10 m length and 1 m width for each still, with cover of standard glass. At the exit, a sea water cooled

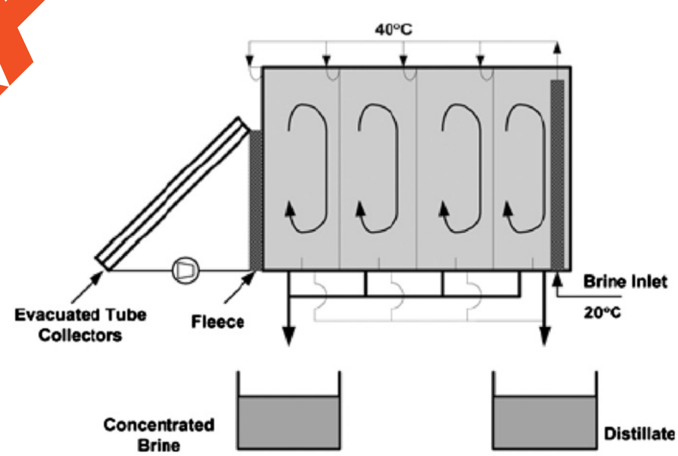


Fig. 30. Multi-effect still: technology for the desalination of 10 m^3/d of water [4].

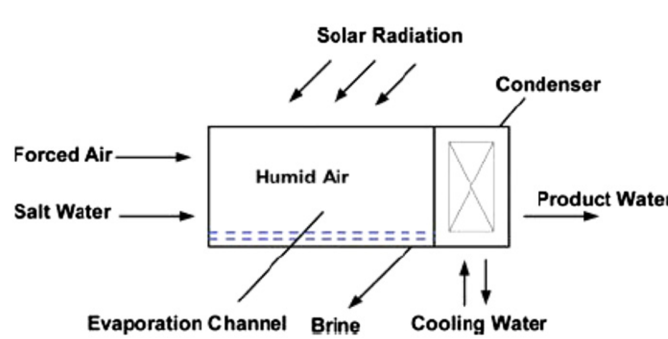


Fig. 31. Flow diagram of forced convection solar distillation [4].

condenser was present and fans induced the forced flow of air. Feed water and air flow rates as well as water temperature (at three different points along the still) and air temperature and humidity were measured. Ambient temperature and humidity, wind velocity and solar irradiance were also measured at the experimental site. The model results compare favorably with experimental data obtained at the pilot plant. The relationship between different parameters was determined, and optimum operating values were selected in the study.

11.4. *Multi-effect humidity process (MEH)*

11.4.1. *Principle of MEH*

The principle of MEH plants is the distillation under atmospheric conditions by an air loop saturated with water vapor. The air is circulated by natural or forced convection (fans). The evaporator-condenser combination is termed a "humidification cycle" because the air flow is humidified in the evaporator and dehumidified in the condenser. The term "multiple effect" used here is not in reference to the number of constructed stages, but to the ratio of heat input to heat utilized for distillate production (GOR > 1).

As noted earlier, efficient evaporation and condensation can be achieved at high temperature (close to 100 °C); however, the thermal efficiency even for the highest quality flat-plate collector drops significantly at such elevated temperatures. On the other hand, at moderate operating temperatures, intensive heat and mass transfer must be maintained in the evaporator and condenser. This necessitates the development of a new generation of solar desalination units.

In recognition of this fact, extensive research has been carried out at different research institutes in Germany [4], to develop more efficient utilization of solar energy for water desalination.

The MEH process further extends the concept of forced convection solar still by separation of the heat collection and evaporation units. The University of Arizona, based on research work performed from 1956 to 1963, initiated construction of a pilot solar energy MEH plant in 1963. The plant was constructed to test the feasibility of using solar energy as a heat source in a humidification system. Further work was initiated in 1964 by the University of Arizona in cooperation with the University of Sonora, Mexico, whereby a larger pilot-scale solar desalting plant at Puerto Penasco, Sonora, Mexico was constructed. The MEH process was developed over the years and a few units constructed and tested in different countries.

They are of two types: the open-water/closed-air cycle and open air/ closed-water cycle described below.

One of the most recent designs of a four-effect still as shown in Fig. 31. The unit was constructed with an active evaporation cross-section of 1.7 m^2 and the heating and cooling cycles. This multi-effect still unit was tilted by a very small angle of around 3–5° from the vertical line. A heat exchanger was used to provide the necessary heat. The GOR increases by up to 80% due to heat recovery from the distillate latent heat. Also, a distillate output in the first effect was 50% higher than the measured values when the feed temperature was raised to 90 °C[4].

11.4.2. *MEH units based on the open-water/closed-air cycle*

In these plants, heat is recovered by air circulation between a humidifier and a condenser using natural or forced draft circulation. As shown in Fig. 32 [4], the saline water feed fed to the condenser is preheated by the evolved latent heat of condensation of water. This heat is usually lost in the single-basin still. The saline water leaving the condenser is further heated in a flat-plate solar collector and then sprayed over the packing in the humidifier. Some of the MEH units used an integrated collector, evaporator, and condenser. The reported efficiency of these desalination units was significantly higher than that of a single-basin still. These types of desalination units are very suitable for small production capacities in remote areas. The process is easy to operate and maintain and it does not require skilled operators.

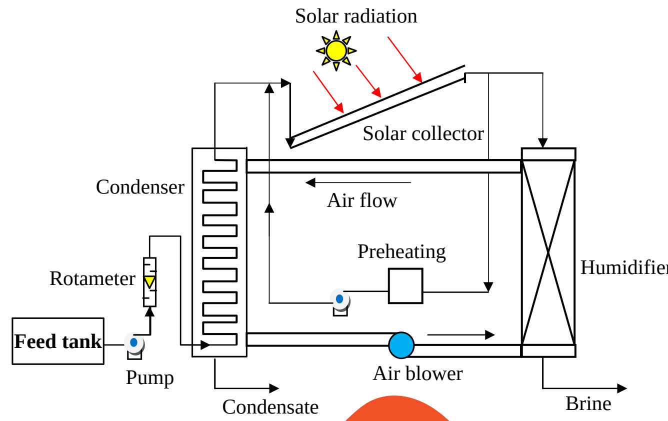


Fig. 32. Schematic diagram of an experimental MEH desalination unit operated with forced or natural air circulation [4].

A performance study of a solar MEH unit installed in the south of Tunisia for potable water production and irrigation was carried out [3]. Several tests on storage, evaporation, and condensation were carried out, and an estimation of the cost of fresh water production was also given. The study showed that the plant, which was intended to produce 12 l/m^2 d of fresh water, did not reach its goal. The highest production was about 6 l/m^2 d, which is only marginally higher than that of the efficient single-basin still.

An MEH plant was constructed [4], which uses natural-draft air circulation. Textile heat exchangers were used for efficient evaporation and condensation with minimum pressure drop. A GOR value higher than 3 was reported.

A techno-economic investigation of an air H-DH desalination process was performed [4]. The results showed that 76% of the energy consumed in the humidifier is recovered by condensation. Their cost calculations showed that the HD process has significant potential as an alternative for small-capacity desalination plants and allows operation of systems with an output as low as 10 m^3/d. An increase in desalination productivity was achieved by increasing the water temperature at the inlet to the humidifier of the MEH unit. Also, air circulation was found essential for raising the system performance. A test rig of an MEH solar desalination plant working on the humidification principle was constructed [4]. The unit yielded 0.63–1.25 l/m^2 h of fresh water on a typical summer day at noontime (2.5–5 l/m^2 d for a 4-h/d peak time operation), which is as low as some efficient single-basin stills.

During the period 1990–1996, Parekh et al. [4] built three MEH desalination units in Iraq, Jordan, and Malaysia. The unit constructed in Iraq was operated with forced air circulation as shown in Fig. 32, while the unit constructed in Jordan was operated with both forced and natural draft air circulation [4]. Based on the experience of operating these units, a third unit operated with natural draft air circulation was constructed in Malaysia [4]. These units were built with a single stage for the purpose of generating sufficient information to construct a rigorous mathematical model that can be used in the design and simulation of such units and also to optimize the performance of existing MEH units. The design and performance simulation of these units is discussed in detail in a previous publication [4].

The Bavarian Center of Applied Energy Research and T.A.S. GmbH & Co. KG at Munich, Germany, has addressed the performance optimization of a MEH unit built in the Canary Islands in Spain. The unit was based on a patent design developed at the University of Munich, as described earlier. The design of the unit was similar to that used by Farid et al. [19] except that the humidifier and condenser were kept in the same unit and the unit was designed for higher capacity. The design of these two units was based on natural convection and not forced convection. After installation, their long-term performance was measured from 1992 to 1997.

These distillation units illustrate the energy saving procedure of MEH. Water is evaporated at ambient pressure and condensed where more than 70% of the heat of evaporation can be recovered. The performance of the units has been improved over the years, and an average daily production of 100 L from an 8.5 m^2 collector area (11.8 L/m^2 d) was obtained without thermal storage.

An MEH unit as shown in Fig. 33 was studied [3]. The desalination plant consists of a solar collector, which provides the thermal energy, and a desalination module that uses multi-effect distillation to treat the water. Seawater fed to the unit evaporates under ambient pressure, and the saturated air is transported by free convection to the condenser area where it condenses on the surface of the plastic heat exchanger. The evaporator consists of vertically suspended tissues or fleece made of polypropylene over which the hot seawater is normally distributed. In the evaporator, partial evaporation cools the brine, which leaves the evaporation unit concentrated at a temperature of about 45 °C. The condenser is a polypropylene bridged double-plate heat exchanger through which the cool brine is pumped upwards. The condensate runs down the plates and trickles into a collecting basin. The heat of condensation is mainly transferred to the cold brine, as it flows upwards inside the heat exchanger. The temperature of the brine rises from 40 °C to about 75 °C. The brine is then heated to the evaporator inlet temperature, which is between 80 and 90 °C by a heat source such as the highly efficient solar collectors, by heat from the thermal storage tank, or by waste heat. Salt content of the brine as well as condenser inlet temperature can be increased by a partial reflux from evaporator outlet to brine storage tank. If re-circulated,

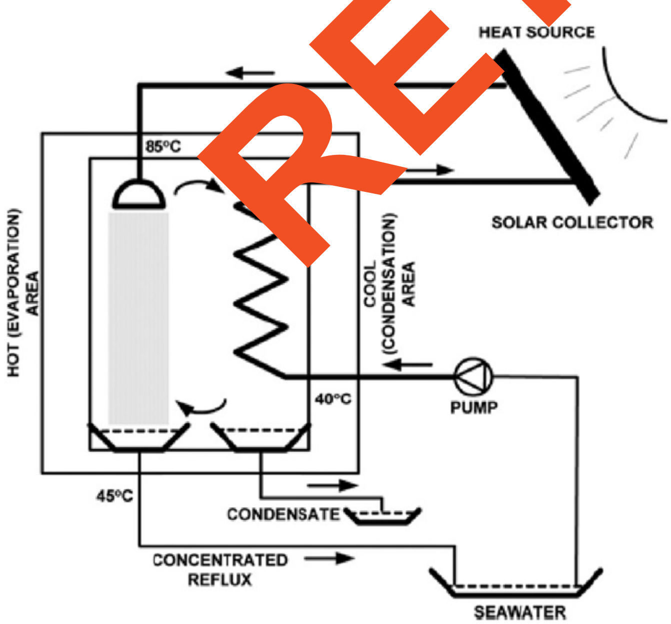


Fig. 33. Illustration of a multi-effect distillation unit without storage implementation [4].

brine needs to be cooled, e.g., by sending the feed water through a cooler before it reaches the condenser. Based on this concept, a pilot plant with direct flow through the collectors has been working almost without any maintenance or repair for a period of more than 7 years on the island of Fuerteventura [4]. Results from Fuerteventura for a distillation unit without thermal storage showed that the daily averaged heat recovery factor (GOR) was between 3 and 4.5. A similar distillation unit in the laboratory at ZAE Bayern yielded a GOR of more than 8 at steady-state conditions [4]. The optimized module produced 40 L/h of fresh water, but it was shown that a production of 1000 L/d is possible when the unit was operated continuously for 24 h. Based on a collector area of 38 m^2, the daily productivity of the optimized module works out to be about 26 L/m^2 of collector area for a 24-h run and with thermal storage under optimized laboratory conditions.

It was realized that an improvement in the overall system efficiency could be reached by adding a thermal storage as alternate heat source to enable 24-h operation of the distillation module. This was achieved by using extra collectors and hot water storage tanks. In a related study, the concept of a solar thermal desalination plant with a heat storage tank installed was investigated.

A unit was constructed in 199[illegible] in Tunisia, with the financial support of the German Ministry of Economic Cooperation and Development (BMZ). In addition, a unit for drip-irrigation was implemented to reduce the water consumption. A new concept was developed and implemented in Sfax, Tunisia, which includes the use of a conventional heat storage tank and heat exchange between the collector circuit (desalted water) and the distillation circuit. This enabled continuous (24 h/d) distillate production. A major factor prompting a 24-h/d operation of these units was the realization that the major capital cost of these units is due to the condenser and humidifier. It was suggested to include a 2 m^3 storage tank in the MEH unit constructed in Tunisia, which uses 38 m^2 collectors, to improve its performance.

A similar suggestion was made to extend the operation of the unit constructed in Jordan and Malaysia to be operated in a 24-h/d mode [4].

11.4.3. MEH units based on the open-air/closed-water cycle

In the study of multi-effect processes, a description of a closed-water circulation system was presented, as shown in Fig. 34. The closed-water circulation is in contact with a continuous flow of cold outside air in the evaporation chamber. The air is heated and loaded with moisture as it passes upwards through the falling hot water in the evaporation chamber. After passing through a condenser cooled with cold seawater, the partially dehumidified air leaves the unit, while the condensate (distillate) is collected. Water is recycled or re-circulated. Incoming cold air provides a cooling source for the circulating water before it re-enters the condenser. This system with a closed salt water cycle ensures a high utilization of the salt water for fresh water production. In the closed water cycle, the salt water is continuously evaporated in the evaporation chamber. For example, 1 m^3 saltwater with 1% salt results in 330 l distillate water and a brine concentration as high as approximately 15% [3].

In further research, some investigators applied an open-air cycle for obtaining good productivity [4]. The air is vented to the atmosphere after its partial dehumidification in the condenser, condenser, while the water is circulated in a closed cycle. The productivity of the units working on this principle was high, but the power required for air circulation was also very high. The system consisted of a humidifier, a solar still in the form of a flow channel, a condenser, and a pond. The solar still was a long glass-covered channel about 200 m long. Sensitivity studies carried out

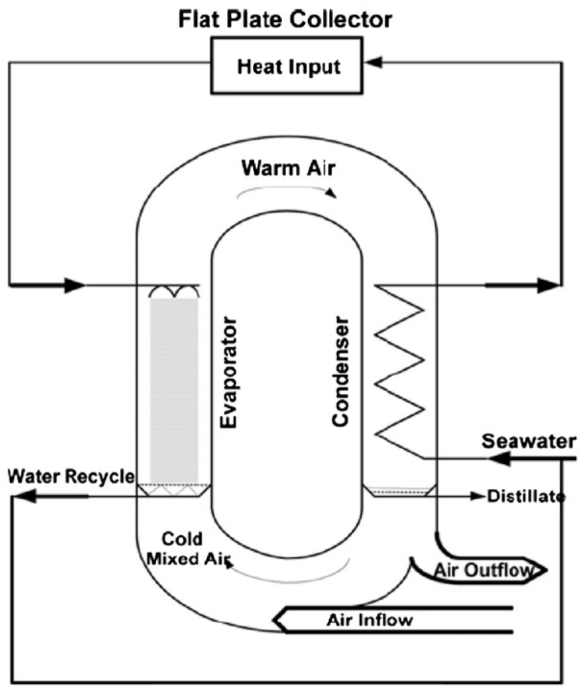


Fig. 34. MEH unit with open-air/closed-water cycle [4].

on the channel still explored parameters such as wind velocity, air flow rate and inlet water temperature and flow rate. The channel selected had a length of 177 m and a width of 1.69 m. Vertical dimensions chosen was 0.31 m × 0.76 m. The performance increased with increasing air flow rate but practically leveled off at about 2500 kg/h.

Recently, an MEH unit based on this principle was built at Kuwait University [4]. It received energy from a salinity gradient solar pond of 1700 m² in area, used to load the air with humidity. The water is then collected by cooling the air in a dehumidifying column, producing 9.8 m³/d of distillate.

In a similar study a solar-operated H–DH desalination system was described, which consisted of a solar pond, a humidifying column, a dehumidifying stack and necessary fans and pumps. For an average 21,000 kJ/m² solar intensity and 22% efficiency, a heat rate of 90.9 kW thermal energy can be obtained for the 1700 m² solar pond built at Kuwait. A performance ratio of 3 (or 800 kJ/kg distillate) is attainable mentioned in the study, with an output of 3 m³/d.

The process described by …ll [22], as discussed earlier, where the moist air is passed over a cooling coil of an air conditioner, falls under the open-air/closed-water cycle MEH category. He noted that the method might be economical only if the produced fresh water was considered as an air-conditioning by-product.

Also, an MEH unit operated in an open-air was built [4], closed water cycle. The unit was 1 m × 1 m × 1.5 m in dimension and was capable of producing up to 100 L/h of fresh water. They replaced the collector by a boiler to provide the hot water, which was sprayed at the surface of honeycomb packing of the humidifier. A fan was used to force the process air to flow through the humidifier in a cross flow arrangement. The hot humid air was then passed through a condenser, cooled by cold seawater prior to feed to the boiler. The seawater captures some of the latent heat of condensation thereby improving the efficiency of the unit. The water from the humidifier was recycled to the storage tank since it is warm and its salinity is not very high. However, some bleeding of this water was required to prevent the accumulation of salt in the unit. An efficiency of 80% was obtained using hot water feed from a boiler. This corresponds to about 68% only when a solar collector is used. The unit production did not exceed 6.2 l/m² d. The authors showed a strong effect of the humidifier feed water temperature, which has been reported previously in all types of MEH units. The effect of air flow rate on the production efficiency showed a maximum value. Increasing air flow rate first increases the heat and mass transfer coefficients in the humidifier and condenser but eventually lowers the operating temperature. This is the reason for the maximum efficiency observed.

Another MEH unit based on an open-air cycle—and referred to as "dew vaporation"—was built at Arizona State University for the production of 45.4 kg/d of condensate, with GOR values in excess of 7.5. The evaporator unit was constructed out of strips of thin, water-wettable plastics and was operated at a low-pressure drop. This system, studied and experimentally operated by Beckman [23], could emerge as economically feasible for small-capacity plant applications. As mentioned in his study, RO technology faces competition from other seawater desalination techniques such as MED, MSF and MEH with and without thermal vapor compression. The electrically driven MVC plants consume more electricity than RO plants. The thermally driven plants attempt to recycle the applied heat continually to minimize the operating cost. The energy reuse factor economically varies from 6 to 12. The optimum GOR value depends on factors such as plant capacity, cost of energy, cost of materials, interest and tax rates.

12. Other processes based on humidification–dehumidification

Other studies carried out on desalination systems based on the H–DH principle are described in the following sections. Although all these processes are based on the H–DH principle, the respective researchers have presented them under different process titles and descriptions.

12.1. Solar multiple condensation evaporation process

In 1991, a desalination process based on a solar multiple condensation evaporation (SME) cycle was studied, and in further related studies, a study of a water desalination installation using the solar multiple condensation evaporation cycle (SMCEC) was presented [4]. It is mentioned that the number of heat recovery cycles depends on the condenser surface area and temperature of the cooling water. A collector efficiency of 58% and a water temperature of 65–75 °C can produce 6 l/m²d of condensate based on 1 m² collector and condenser surface areas.

Tests in Sfax, Tunisia, produced condensate of 4 l/m²d with a collector efficiency of 46% (theoretical 14.3 l). Two types of desalination units—namely SME 3.6 and SME 200 were manufactured by Aquasolar GmbH & Co., and Aquasolar (Tunisia) in the presentation by Graef. The SME 3.6 is most suitable for a single family, producing up to 50 L/d, and has been in series production since 1991 in Tunisia [4].

The SMCEC-based desalination unit belongs to a new generation of decentralized installations for water desalination using solar energy with heat recuperation was presented. Similar to the solar HD and MEH units, the SMCEC-based units are well suited for developing countries with extended rural areas because of their simplified design, low maintenance, extended life-time (over 20 years), almost zero energy consumption and low capital cost [4].

A detailed modeling, simulation and experimental validation for this type of installation permits the optimization of size of the solar collectors, evaporation tower and condensation tower

(similar to the modeling and simulation for an MEH unit studied and presented in the study by Farid et al. [19]. The SMCEC-based desalination unit consists of three main parts: solar collector, condensation tower and evaporation tower. The flat-plate collector is equipped with an absorber made of polypropylene material covered by a Hostoflan membrane or glass. The absorber is made up of very thin and tightly spaced capillary tubes where the salty water circulates. The evaporation tower produces the water vapor. Thorn trees are utilized to increase the water spray and improve evaporation. At the beginning, the brackish or seawater is heated by the solar collector. Then, hot water is injected into the top of the evaporation tower. An atomizer with a special shape is used to insure a uniform pulverization of the hot water in all the sections of the tower. Air circulation in the evaporation is possible either by natural or forced convection.

To examine the validity of the model proposed by Ben Bacha et al. [16], experimental measurements were taken using the pilot desalination unit located at the National School of Engineering of Sfax, Tunisia. The specifications of the pilot unit are: solar collector with an area of 7.2 m^2 (effective transmission absorption of 0.83 and loss coefficient 3.73 $W/m^2\,K$), evaporation tower size of 1.2 m × 0.5 m × 2.55 m, with solid packing of thorn trees, and a condensation tower of size 1.2 m × 0.36 m × 3 m. Based on model simulation and experimental validation, the optimum operation and production for the SMCEC unit require a perfect insulation of the unit, a high water temperature and flow rate at the entrance of the evaporation tower, a low water temperature at the entrance of the con-denser, hot water recycling by injection at the top of the evaporation chamber, and a storage tank to store the hot water excess that would extend water desalination beyond sunset.

12.2. Aero-evapo-condensation process

Bourouni et al. [20] conducted an experimental investigation with a desalination plant using the "aero-evapo-condensation" process. The unit consists of a falling film evaporator and a condenser made of polypropylene, and is designed to work at low temperatures (70–90 °C), specifically using geothermal energy. The prototype was patented by the firm [illegible]aldor-Marseille (France) in 1994. This prototype includes two cross-flow heat exchangers, a horizontal falling film evaporator, and a horizontal falling film condenser. The two exchangers were made of polypropylene and affect the humidification–dehumidification of air. The influence of the various thermal and hydrodynamic parameters on the unit performance was investigated. Results showed that the performance of the unit increased with the increase of inlet hot water and air temperature. On the other hand, it was observed that the performance of the unit decreased when the air velocity and hot liquid flow rate increased. A critical film flow rate corresponding to the film breakdown was determined. At this value, a maximum amount of evaporated water was obtained. Horizontal-tube falling film evaporators have an advantage over vertical-tube evaporators in dealing with problems such as liquid distribution, leveling, non-condensable gases on the tube side, fouling and liquid entertainment. Another parameter affecting the heat transfer coefficients is the water distribution system at the top of the horizontal tube. Instead of the common "perforated-plate" water distribution system, the more accurately controlled "thin-slot" water distribution system was shown to be preferable.

12.3. Carrier gas process

Results of the "carrier-gas process" (CGP) of EvCon Corp. have presented [4], which demonstrated a potential for desalination of seawater and brackish water and for the concentration of various process streams and industrial wastewaters. It operates at temperatures below the normal boiling point and at ambient pressure. This process is similar to the HD process with two chambers (one for evaporation and the other for condensation) being physically separated by a common heat-transfer wall. The CGP process provides results over a wide range of performance ratios and production densities simply by varying the temperatures and airflows. The system can also be operated using renewable heat supplies including solar and ambient air. Thus, this system too is a convenient choice for remote and arid regions of the world where conventional technology is too expensive.

An organization formed by engineers and architects based in Barcelona (ECOTERM [3]), claim to be developing a pilot plant for desalination using the CGP. This principle is similar to the HD technique and has been studied separately as an alternative desalination process. Expected results from the proposed pilot unit include a product water flow rate of 1 [illegible]/h for an air flow rate of 7.55 kg/h and a heat exchange surface area of 500 m^2. The possible plant sizes suggested are for productivity between 100 l/h and 1000 m^3/h [illegible] high[illegible]. Capability to work with low temperatures of approximately 40 °C and using forms of energy such as residual heat of cogeneration, solar energy, and geothermal energy are also possibilities for this proposed unit.

12.4. Summary of studies conducted on the HD desalination process

Almost all the investigators state that the effect of water flow rate on the performance of the unit is important. The effect of air flow rate on productivity is termed insignificant by almost authors [illegible]. Almost all researchers express a preference for natural convection since air flow rate has an insignificant effect on unit productivity. However, forced circulation could be feasible with another cost-effective source of energy such as wind energy. The effect of air flow rate is only noticeable at temperatures around [illegible]0 °C, as reported by Al-Hallaj et al. [24].

Another variable tested was the packing material in the humidifier. Packing material should generally be of such a size and shape as to provide a high contact surface and a low pressure drop. The choice of packing material tends to have an effect on the thermal efficiency and productivity of the unit. Examples include Raschig rings, Berl saddles, Pall rings, Lessing rings, Prym rings, meshed curtains, wooden slats, wooden shavings, and fleece made of polypropylene or honey-comb paper as used by some researchers.

13. Summary of studies conducted on extracting water from moist air

Different technological processes are proposed by numerous investigators to extract water from the ambient air using solar energy as a power source. The flow diagram of technological processes of separation of water from moist air using solar energy [25] is demonstrated in Fig. 35.

Hamed et al. [26] explained different methods to extract water from the moist air. Abualhamayel and Gandhidasan [11] studied system for water recovery from air. They used a desiccant system shown in Fig. 3. The system consists of a flat, blackened, tilted surface and is covered by a single glazing with an air gap of about 45 cm. The bottom of the unit is well insulated. At night, the strong absorbent flows down as a thin film over the glass cover in contact with the ambient air. If the vapor pressure of the strong desiccant is less than the vapor pressure of water in the atmospheric air, mass transfer takes place from the atmosphere to the absorbent. Due to absorption of moisture from the ambient air during the night, the absorbent be-comes diluted. The water-rich

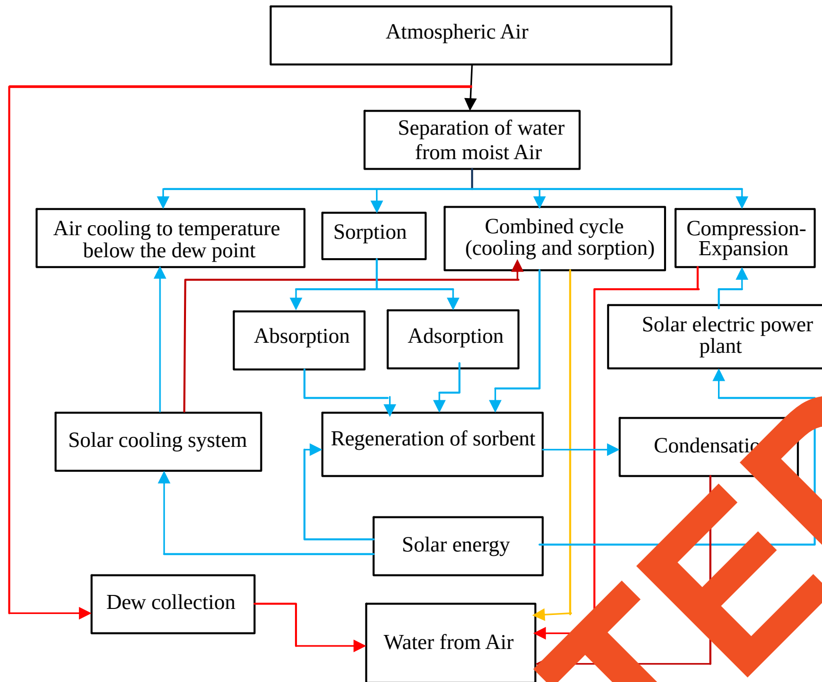


Fig. 35. Flow diagram of technological process of separation of water from moist air using solar energy [25].

absorbent must be heated during the day to recover the water from the weak absorbent. Therefore, during the day, the weak desiccant flows down as a thin film over the absorber surface. The weak absorbent is heated by solar energy, and the water that evaporates from the solution rises to the glass cover by convection where it is condensed on the underside of the glass cover and the absorbent leaving the unit becomes strong. The performance of the unit at night depends on the potential for mass transfer, which is the difference in water vapor pressure between the ambient air and desiccant.

In desert regions, mixing a sandy layer on the ground surface with desiccant as a promising method to minimize the cost of the vapour absorption bed was proposed. Hamed [27] and Kabeel [13] introduced a method to extract water from moist air by using a sandy bed solar collector. The proposed methodology was studied theoretically and experimentally to evaluate the system performance. In that methodology an impregnated bed with 30% concentration $CaCl_2$ is used. That study reported that, the system could provide up to [illegible] of fresh water per square meter of glass cover per day. Another study studied the capability of the pyramid glass cover with a multi-shelf to extract water from humid air [28].

The continuous production of water from air, during 24-hour, requires more compact adsorption units. For that unit, the application of forced convection adsorption is adopted by Hamed [29]. Also, that unit employed a packed porous bed

Ahmed Sultan 2004 introduced a non-conventional method to extract water from atmospheric air during 24-hours. A compact system was studied during that methodology.

Air cooling method for water extraction from air was conducted analytically by Khalil [22] for the climatic conditions of UAE coastal regions, and it was reported that the quantity of fresh water obtained depends on the properties of humid air, air velocity, cooling coil surface area, and the heat exchange arrangement. Description and analysis of the theoretical cycle for absorption of water vapor from air with subsequent regeneration, by heating is presented by Hamed [30].

The application of solar concentrator for fresh water production from the atmospheric air was studied by many researchers. The results were used for assessing the use of solar trough concentration plants for applications other than heating and cooling, in particular for the production of fresh water for human consumption and for agriculture.

On clear nights, the moisture in the air begins to condense on any surface where the temperature has fallen below the dew point temperature. Many parameters effect on the dew point temperature like cloudiness, surface temperature, air humidity, and wind speed. The water is collected by this method whenever humid air and clear night time skies exist simultaneously (Al-Hassan 2009 [32]; Jacobs et al., 2008 [34]).

Aristov et al. [31] developed a selective water sorbents for fresh water production from the atmosphere, the results of their lab-scale tests have demonstrated a feasibility of fresh water production with an output of 3–5 t of water per 10 t of the dry sorbent per day. The selective composite adsorbent for solar-driven fresh water production from atmospheric air is presented before (Wang et al., 2007) that study was synthesized by a patented ultra-large pore crystalline material MCM-41 as host matrices and calcium chloride as a hygroscopic salt. That study introduced productivity more than 1.2 kg fresh water per square meter of the solar collector area.

The water can be collected from air by direct cooling to a temperature lower than the dew point. A typical study was conducted analytically for the climatic conditions of UAE coastal regions; the results reported that the quantity of fresh water obtained, by cooling method, depends on the properties of humid air, air velocity, cooling coil surface area, and the heat exchange arrangement. The limits of water production from atmospheric air were investigated [32]. In this investigation, hot humid air is cooled over refrigeration evaporator coils hence the air is directed to an open localized area. This procedure is considered as a judge of the limited amounts of potable water at a free cost since the obtained water is a by-product during the climate conditioning process.

Hamed et al. [7] investigated the performance of a solar powered desiccant/collector system at the climatic conditions of El-Taif area, Saudi Arabia to extract water from air. The experimental measurements estimated that about 1.0 l pure water per m^2 of glass cover area can be produced.

A non-conventional system to collect water from air based on an adsorption–desorption process using a solid desiccant was constructed [6]. A project called Dew Equipment for Water (DEW) was initiated for a 15.1 m^2 roof for dew collection Measurements of both rain and dew water were performed over several years. Results showed that dew water contributed significantly, 26% of the total collected water

The need for economical realization of solar-desiccant systems for water production in arid areas is of great importance. In desert regions, mixing a sandy layer of the ground surface with desiccant as a promising method to minimize the cost of the vapor absorption bed was proposed (Hamed, 2000 [29]).

A comparative summary of Studies conducted on extracting water from moist air is given in Table (15) [3–37].

14. Economic analysis

The economic analysis made in this section is based on the use of the life cycle cost (LCC). The life cycle cost is an economic assessment of the cost for a number of alternatives by taking into account all significant costs over the lifetime of each alternative, adding each option's costs for every year and discounting them back to a common base. These costs can be categorized into two types: (i) recurring cost (operation cost for the DG and maintenance cost for the DG, the PV generator and batteries) and (ii) non-recurring cost (batteries and DG replacement costs).

15. Conclusion

A comprehensive review of the AWVP techniques and the various water extraction from air units based on this principle has been presented in this study. Solar recovery based on this technique has not yet to be commercially implemented. A detailed review of other desalination processes based on the HD principle would also help in improving the design of current solar-based HD units.

Atmospheric water vapor recovery for human needs, not yet exploited on a large scale, could become reality in the future. Although at present only small amounts of water are recovered, this method is interesting as water could be obtained even in arid regions, including deserts. Perhaps one day an optimal condensation process will be found, making potable water inexpensive and ecological.

Solar humidification dehumidification desalination technology has been reviewed in detail in this paper. From the present review it is found that among all H–DH systems, the multi effect CAOW water heating system is the most energy efficient. For this system, the cost of water production is ~US $ 3–7/m^3 [10]. Even though this is higher than that for RO systems working at similarly small capacities (5–100 m^3/day), the H–DH system has other advantages for small-scale decentralized water production. These advantages include much simpler brine pretreatment and disposal requirements and simplified operation and maintenance. Methods to further improve the performance of the H–DH cycle have also been proposed in this paper. These methods include sub-atmospheric and multi-pressure operations. Further research needs to be carried out to realize the full potential of these ideas and the H–DH concept in general.

Appendix-A. Equations describing the physical properties of moist air [8].

A.1. Water vapor pressure

– Saturation vapor pressure, P_s, in pascals:

$$P_s = 610.78 \times \exp(t/(t+238.3) \times 17.2694) \tag{A1}$$

where, t is the temperature in degrees Celsius

– The saturation vapor pressure below freezing can be corrected after using the equation above, thus:

$$P_s \text{ ice} = -4.86 + 0.855 P_s + 0.000244 {P_s}^2 \tag{A2}$$

– The next formula gives a direct result for the saturation vapor pressure over ice:

$$P_s \text{ice} = \exp(-6140.4/(273+t)+28.916) \tag{A3}$$

– The dew point can be calculated from the actual vapor pressure (P_V) by

$$T_{dp} = (238.3 \times \ln(P_v/610.78))/(17.558 - \ln(P_v/610.78)) \tag{A4}$$

The pascal is the SI unit of pressure = Newton/m^2. Atmospheric pressure is about 100,000 Pa (standard atmospheric pressure is defined as 101,300 Pa).

Water vapor concentration

The relationship between vapor pressure and concentration is defined for any gas by the equation

$$P = nRT/V \tag{A5}$$

P is the pressure in Pa, V is the volume in cubic meters, T is the temperature in degrees Kelvin (degrees Celsius + 273.16), n is the quantity of gas expressed in molar mass (0.018 kg in the case of water), R is the gas constant: 8.31 Joules/mol/m^3.

To convert the water vapor pressure to concentration in kg/m^3: (Kg/0.018)/V = P/RT.

$$\text{kg/m}^3 = 0.002166 \times P/(t+273.16) \tag{A6}$$

where p is the actual vapor pressure

Relative humidity

The Relative Humidity (RH) is the ratio of the actual water vapor pressure to the saturation water vapor pressure at the prevailing temperature.

$$\text{RH} = P/P_s \tag{A7}$$

RH is usually expressed as a percentage rather than as a fraction. In the biological literature, however, the RH is often expressed as a fraction and is then called the water activity.

The RH is a ratio. It does not define the water content of the air unless the temperature is given. The reason RH is so much used in conservation is that most organic materials have an equilibrium water content that is mainly determined by the RH and is only slightly influenced by temperature.

Notice that air is not involved in the definition of RH. Airless space can have a RH. Air is the transporter of water vapor in the atmosphere and in air conditioning systems, so the phrase"RH of the air" is commonly used, and only occasionally misleading. The independence of RH from atmospheric pressure is not important on the ground, but it does have some relevance to

calculations concerning air transport of works of art and conservation by freeze drying.

The dew point temperature

The water vapor content of air is often quoted as dew point. This is the temperature to which the air must be cooled before dew condenses from it. At this temperature the actual water vapor content of the air is equal to the saturation water vapor pressure. The dew point is usually calculated from the RH. First one calculates P_s, the saturation vapor pressure at the ambient temperature. The actual water vapor pressure, Pa, is:

$$P_a = P_s \times RH\%/100 \tag{A8}$$

The next step is to calculate the temperature at which pa would be the saturation vapor pressure. This means running backwards the equation given above for deriving saturation vapour pressure from temperature: Let $w = \ln\,(P_a/610.78)$.

$$T_{dp} = w \times 238.3/(17.294 - w) \tag{A9}$$

This calculation is often used to judge the probability of condensation on windows and within walls and roofs of humidified buildings.

The dew point can also be measured directly by cooling a mirror until it fogs. The RH is then given by the ratio

$$\mathrm{RH} = 100 \times P_s dewpoint/P_s ambient. \tag{A10}$$

Concentration of water vapor in air

It is sometimes convenient to quote water vapor concentration as kg/kg of dry air. This is used in air conditioning calculations and is quoted on psychometric charts. The following relations for water vapor concentration in air apply at ground level. Dry air has a molar mass of 0.029 kg. It is denser than water vapor which has a molar mass of 0.018 kg. Therefore, humid air is lighter than dry air. If the total atmospheric pressure is P_{tot} and the water vapor pressure is P_{wv}, the partial pressure of the dry air component is $P_{tot} - P_{wv}$. The weight ratio of the two components, water vapor and dry air is:

$$\text{kg water vapour/kgdry air} = 0.018 \times P_{wv}/(0.029 \times (P_{tot} - P_{wv})) = 0.62 \times P_{wv}/(P_{tot} - P_{wv})$$

At room temperature $P_{tot} - P_{wv}$ is nearly equal to P, which at ground level is close to 100 000 Pa, so approximately:

$$\text{kg water vapor/kgdry air} = 0.62 \times 10^{-5} \times P_{wv} \tag{A11}$$

Thermal properties of damp air

The heat content, usually called the enthalpy, of air rises with increasing water content. This hidden heat, called latent heat by air conditioning engineers, has to be supplied or removed in order to change the relative humidity of air, even at a constant temperature. This is relevant to conservators. The transfer of heat from an air stream to a wet surface, which releases water vapour to the air stream at the same time as it cools it, is the basis for psychrometry and many other microclimatic phenomena. Control of heat transfer can be used to control the drying and wetting of materials during conservation treatment. The enthalpy of dry air is not known. Air at zero degrees celsius is defined to have zero enthalpy. The enthalpy, in kJ/kg, at any temperature, t, between 0 and 60C is approximately:

$$\mathrm{h} = 1.007\mathrm{t} - 0.026 \tag{A12}$$

$$\text{below zero}: h = 1.005\mathrm{t} \tag{A13}$$

The enthalpy of liquid water is also defined to be zero at zero degrees celsius. To turn liquid water to vapor at the same temperature requires a very considerable amount of heat energy: 2501 kJ/kg at 0C.

At temperature t the heat content of water vapor is:

$$h_{WV} = 2501 + 1.84t \tag{A14}$$

Notice that water vapor, once generated, also requires more heat than dry air to raise its temperature further: 1.84 kJ/kg.C against about 1 kJ/kg.C for dry air. The enthalpy of moist air, in kJ/kg, is therefore:

$$h = (1.007 \times t - 0.026) + g \times (2501 + 1.84 \times t) \tag{A15}$$

g is the water content in kg/kg of dry air

The psychometric

The final formula in this section is the psychrometric equation. The psychometric is the nearest to an absolute method of measuring RH that the conservator ever needs. It is more reliable than electronic devices, because it depends on the calibration of thermometers or temperature sensors, which are much more reliable than electrical RH sensors. The psychometric, or wet and dry bulb thermometer, responds to the RH of the air in this way: Unsaturated air evaporates water from the wet wick. The heat required to evaporate the water into the air stream is taken from the air stream, which cools in contact with the wet surface, thus cooling the thermometer beneath it. An equilibrium wet surface temperature is reached which is very roughly half way between ambient temperature and dew point temperature. The air's potential to absorb water is proportional to the difference between the mole fraction, ma, of water vapor in the ambient air and the mole fraction, mw, of water vapor in the saturated air at the wet surface. It is this capacity to carry away water vapor which drives the temperature down to tw, the wet thermometer temperature, from the ambient temperature ta:

$$(m_{wv} - m_a) = B(t_a - t_w) \tag{A16}$$

B is a constant, whose numerical value can be derived theoretically by some rather complicated physics (see the reference below). The water vapour concentration is expressed here as mole fraction in air, rather than as vapor pressure. Air is involved in the psychrometric equation, because it brings the heat required to evaporate water from the wet surface. The constant B is therefore dependent on total air pressure, P. However the mole fraction, m, is simply the ratio of vapour pressure p to total pressure P: p/P. The air pressure is the same for both ambient air and air in contact with the wet surface, so the constant B can be modified to a new value, A, which incorporates the pressure, allowing the molar fractions to be replaced by the corresponding vapour pressures:

$$P_{wv} - P_a = A \times (t_a - t_w) \tag{A17}$$

The relative humidity (as already defined) is the ratio of pa, the actual water vapor pressure of the air, to P_s, the saturation water vapor pressure at ambient temperature.

$$\mathrm{RH}\% = 100 \times P_a/P_s = 100 \times (P_{wv} - (t_a - t_w) \times 63)/P_s \tag{A18}$$

When the wet thermometer is frozen the constant changes to 56 The psychometric constant is taken from: R.G.Wylie & T. Lalas, "Accurate psychometric coefficients for wet and ice covered cylinders in laminar transverse air streams", in Moisture and

Humidity. These values are slightly lower than those in general use. There are tables and slide rules for calculating RH from the psychomotor but a programmable calculator is very handy for this job. Psychometric charts have graphical versions of all these formula and don't need electricity.

To check your program, take air at 20C and 15.7C wet bulb temperature. The RH is 65%. The water vapor pressure is 1500 Pa. The water vapor concentration in kg/m^3 is 0.011, in kg/kg it is 0.009. The dew point is 13 °C.

References

[1] Shanmugam, G, Jawahar, GS, Ravindran, S. Review on the uses of appropriate techniques for arid environment. International Conference on Water Resources and Arid Environment, 2004.

[2] El-Dessouki HT, Ettouney HM. Fundamentals of salt water desalination. Elsevier Science B.V; 2002.

[3] El-Ghonemy AMK. Water desalination systems powered by renewable energy sources: review. Renewable and Sustainable Energy Reviews 2012;16: 1537–56.

[4] Parekh S, Farid MM, Selman JR, Al-Hallaj S. Solar desalination with a humidification–dehumidification technique—a comprehensive technical review. Desalination 2004;160(2004):167–86.

[5] Beysens D, Milimouk I. The case for alternative fresh water sources pour les ressources alternatives en eau. Sécheresse 2000;11:4.

[6] Roland V, Wahlgre N. Atmospheric water vapour processor designs for potable water production: a review. Water Research 2001;35(1):1–22.

[7] Hamed AM, Aly AA, Zeidan EB. Application of solar energy for recovery of water from atmospheric air in climatic zones of Saudi Arabia. Natural Resources 2011;2:8–17.

[8] Sultan A. Absorption/regeneration non-conventional system for water extraction from atmospheric air. Renewable Energy 2004;29:1515–35.

[9] ASHRAE Handbook of Fundamentals. American Society of Heating, Air-Conditioning and Refrigerating Engineers, Inc. (ASHRAE), Atlanta, GA.

[10] Prakash G, Narayan, Sharqawy MH, Summers EK, John H. The potential of solar-driven humidification-dehumidification desalination for small-scal[illegible] decentralized water production.Elsevier; 2010.

[11] Abualhamayel HI, Gandhidasan P. A method of obtaining fresh water from the humid atmosphere. Desalination 1997;113:51–63.

[12] Gad HE, Hamed AM, El-sharkawy II. Application of solar desicca[illegible]llector system for water recovery from atmospheric air. Renewable En[illegible];22: 541–56.

[13] Kabeel AE. Application of sandy bed solar collector [illegible]em fo[illegible]ater extraction from air. International Journal of Energy Re[illegible]ch [illegible] 381–94.

[14] Bardi U. Fresh water production by means o[illegible]lar concen[illegible]on: the AQUASOLIS project. Desalination 2008;220:58[illegible]

[15] Etan Bar. Extraction of water from air an[illegible]erna[illegible] solution for water supply. Desalination 2004;165:335.

[16] Ben-Bacha H, Damak T, Bouzguenda [illegible] Experimental [illegible]dation of the distillation module of a desalinati[illegible] station using the S[illegible]EC principle. Renewable Energy 2003;28:2335[illegible]

[17] Müller-Holst H, Engelhardt M, [illegible]ve[illegible] Scholkopf W. Solar thermal seawater desalination systems for [illegible]tralized[illegible]e. Renewable Energy 1998;14(1–4):311–8.

[18] Chafik E. A new type [illegible]eaw[illegible] desal[illegible] plants using solar energy. Desalination 2003;15[illegible]33–48.

[19] Farid MM, Parekh S, Selman JR, Al-Hallaj S. Solar desalination with a humidification-dehumidification cycle: mathematical modeling of the unit. Desalination 2002;151:153–63.

[20] Bourouni K, Chaibi MT, Tadrist L. Water desalination by humidification and dehumidification of air: state of the art. Desalination 2001;37:167–76.

[21] Beckmann, JR. Method and apparatus for simultaneous heat and mass transfer utilizing a carrier gas, 2005 US Patent no. 6,911,121.

[22] Khalil A. Dehumidification of atmospheric air as a potential source of fresh water in the UAE. Desalination 1993;93:587–96.

[23] Beckman, JR. Innovative atmospheric pressure desalination, 1999. Final Report 98-FC-81-0049.

[24] Al-Hallaj S, Farid MM, Tamimi AR. Solar desalination with humidification-dehumidification cycle: performance of the unit. Desalination 1998;120: 273–80.

[25] EL-Sharkawy I. Production of water by extraction of atmospheric moisture using solar energy, 2000 M.Sc. Thesis, Mansoura University.

[26] Hamed AM, Kabeel AE, E-Shafei Zedin Ayman Aly A. Technical review on the extraction water from atomospheric air in arid zones. Journal of Heat and Mass Transfer 2010;4(3):213–28.

[27] Hamed AM. Experimental investigatio[illegible]tural absorption on the surface of sandy layer impregnated w[illegible]liquid de[illegible]nt. Renewable Energy 2003;28:1587–96.

[28] Kabeel A. Water production from air [illegible] multi she[illegible]s solar glass pyramid system. Renewable energy 2[illegible]32(1):1[illegible]72.

[29] Hamed AM. Parametric stu[illegible]f the adsorp[illegible]ption system producing water from ambient air. [illegible]nation[illegible]urnal o[illegible]ewable Energy Engineering 2000;2:244–52.

[30] Hamed AM. Absor[illegible]ation cy[illegible] for production of water from air—theoretical [illegible]oach. R[illegible]able E[illegible]gy 2000;19:625–35.

[31] Aristov YUI, T[illegible]rev MM, G[illegible], Snytnikov VN, Parmon VN. New composite [illegible] for solar-dri[illegible] technology of fresh water production from the a[illegible]osph[illegible] Solar Energy 1999;66(2):165–8.

[32] Al-hassan GA. Fog w[illegible] collection evaluation in Asia region-Saudi Arabia. W[illegible]ources Manag[illegible]nt 2009;23:2805–13.

[33] [illegible]eebullah BA. Potential use of evaporator coils for water extraction in hot [illegible]d humid areas. Desalination 2009;237:330–45.

[34] [illegible]obs AFG, H[illegible]inkveld BG, Berkowicz SM. Passive dew collection in a g[illegible]land area[illegible]e Netherlands. Atmospheric Research 2008;87:377–85.

[35] Ko[illegible]hi M[illegible] method of obtaining water in arid land. Solar Energy 1963[illegible]

[illegible] Sofrata H. Non-conventional system for water collection. Proc. of Solar [illegible]lination Workshop, 1981, 71–87.

[illegible] Tyg[illegible]nov VV. An equipment for collecting water from air, 1947, Patent no. 69751, Russia.

[illegible]8] Wahlgren RV. Atmospheric water vapor processor designs for potable water production: a review. Water Resources Management 2001;35:1–22.

[illegible]9] Wang G, Ji RZ, Li LX. New composite adsorbent for solar-driven fresh water production from the atmosphere. Desalination 2007;212:176–82.

[40] Elsarrag, E, Al Horr,Y. Experimental investigation on water recovery from the atmosphere in arid humid regions CIBSE Technical Symposium, DeMontfort University, Leicestern UK—6th and 7th September 2011.

[41] Gordeeva LG, Tokarev MM, Parmon VN, Aristov YI. Selective water sorbents for multiple application, fresh water production from the atmosphere. Elseveir 1998;65(1):153–9.

[42] Ben Bacha H, Bouzguenda M, Abid MS, Maalej AY. Modeling and simulation of a water desalination station with solar multiple condensation evaporation cycle technique. Renewable Energy 1999;18:349–65.

[43] Zheng, QR, Pan, QY, Jie, C, Zhi, HJ. Preliminary study of extracting water from air utilizing ship's waste heat from cylinder jacket cooling water. International conference on computer distributed control and intelligent environmental monitoring, 2011.